STUDIES OF COMPATIBILITY AND INVESTIGATIONS OF A MODEL OF REACTION TIME

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SUMMARY

At its inception this research was addressed to a specific area of choice reaction tasks, namely key-pressing situations of extreme compatibility. The apparatus used to evoke maximal compatibility was based on the vibrotactile (VT) apparatus of Leonard (1959) with which he showed that there was no change in reaction time (RT) as the number of alternatives, N, increased from 2 to 4 to 8 after about 500 trials, although simple RT was shorter. This contrasts with the usual finding that RT is proportional to the logarithm of N. The first experiment reported here showed more conclusively than was possible with Leonard's design that subjects do respond with no increase in choice RT with N after relatively little practice, with simple RT again found to be faster. Several explanations of this lack of increase were considered and excluded, but two remained viable:- either there is actually no increase in processing time with N, or a small increase exists, but this processing overlaps other stages which dictate a minimum RT and mask the increase, at least for N up to 8. Data from the VT condition of experiment 2 which used children as subjects, since any increase would be larger for subjects with less spatial location experience, cast doubt on the second suggestion, while the visual stimuli condition supported the premise that children respond like less practised adults.

The most favoured conclusion therefore was that there is no increase in processing time with N in compatible VT situations.

This presents difficulties for many existing choice reaction models.

A further experiment using the VT apparatus in a set of related RT tasks produced results which are difficult to account for by considering the RT process as the aggregate of a sequence of nonoverlapping stages, an idea derived from the subtractive stage hypothesis (Donders 1868, see Koster 1969). Evidence and theory on this hypothesis was reviewed and it was concluded that it is generally too restrictive to be fully correct. Two principles seemed to explain most of the results in this experiment. These were: the temporal uncertainty principle - response inhibition is greater for responses made irregularly in time, which increases RT; and the latent stimuli principle - latent stimuli, i.e. all potential stimuli not given on the current trial, influence RT to the given stimulus.

The inadequacies of current models in fitting these results led to the development of a new model which satisfactorily covers these and previously published results. In essence this model depicts the choice reaction process as a flow of evidence from representations of the potential stimuli along stimulus-response (S-R) association lanes to their corresponding responses. This transformation continues until one of the responses accumulates a preset amount of evidence and is thereby triggered. The duration of the transformation from a stimulus to its response is a function directly of the amount of excitation for that stimulus and inversely with the compatibility or degree of association between it and its response. In addition it is postulated that the rate of transformation increases within each trial. This feature gives the model its name - the accelerating cycle model. The temporary uncertainty principle and the latent stimuli principle are both incorporated in the model. The accelerating cycle model is not inconsistent with the additive stage approach as it can be applied whether RT processing is by serial or by overlapping stages.

Three further experiments showed that assumptions and predictions of the model received good support from the data. Firstly it is shown that the amount of noise is independent of the number of alternatives as the accelerating cycle model assumes, and that the shortest stimulus duration at which subjects achieve asymptotic information transmission values is independent of N. This can be interpreted as indicating that the time to gain a representation of the stimulus sufficient to process accurately is unaffected by N.

The model reconciles the two formulations of the logarithmic relationship between RT and N suggested by Hick (1952a), RT = $k.log(N+1)$, and Hyman (1953), RT = $A + B.log(N)$. Each can be derived as an extreme of the general relationship, RT = $A + B.log\ (N+D)$, where $0 \leqslant D \leqslant 1$, and D equals the internal stimulus strength divided by the response criterion. The final experiment presents evidence in accord with the model's prediction as to the effect of the two parameters determining D.

Overall, the validity of the model's approach is confirmed and it appears to offer a satisfactory alternative to current models. The model is not complete: for example it does not quantify the effect of practice on RT, although it does describe the general decrease found experimentally. It is designed so that other parameters can be incorporated into the model to account for the effect of other variables once the form of their interactions with the parameters currently in the model is fully known.

An earlier form of the model presented in Chapter IV, and the experiments in that chapter, were submitted in partial fulfilment of the requirements for the Honours Degree of B.Sc. in Psychology in the University of Adelaide.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and, to the best of my knowledge and belief, contains no material previously published or written by another person, except when due reference is made in the text.

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CHAPTER I

THE RELATIONSHIP BETWEEN CHOICE RT AND NUMBER OF ALTERNATIVES OR INFORMATION TRANSMITTED

1.1 *General relationship*

Shortly after the development of mathematical communication theory (see Shannon & Weaver 1949), Miller and Frick (1949) advocated its application to psychology in general and choice behaviour in particular. The first experimental analysis showing its usefulness was by Hick (1952a) who found a linear relationship between the mathematical measure of information transmitted, H_t, and choice reaction times when the number of alternative stimuli and responses was varied. This was the case for two sets of data, one from a new experiment of his own and the other presented by Merkel (1885). Hick's experiment used 10 pea-lamps displayed in an approximate circle, each lamp corresponding to one of 10 response keys on which the subject rested his fingers. One lamp came on for each trial, and the subject was told to depress the corresponding key as quickly as possible. Five seconds after the key press the next stimulus came on. Subjects were given batches of trials in which the stimulus set comprised between 2 and 10 lamps (omitting 7 and 9) with each stimulus in the given set occurring with equal frequency. The reaction time, RT, was measured from the onset of the stimulus to the press of the key. The response apparatus was similar in Merkel's experiment, although a key release was the response required, not a key press, while the stimuli were the arabic numerals 1-5 and the roman numerals

I-V appearing one at a time in random order on a rotating drum. Hick found that the RT to a choice between N stimuli was well described by the equation

$$RT = k.Log(N + 1) \tag{1.1}$$

He suggested that the $N + 1$ in this equation reflects the fact that the subject must decide not only which of N alternatives the stimulus is, but whether it is there at all, which effectively adds 1 to his numer of choices. If the subject is certain that a stimulus will be present at a time which he can determine, the choice may revert to a choice between N states representing the different stimuli. Indeed Hyman (1953) suggested that the relationship is more understandable in the form

$$RT = A + B.Log(N) \tag{1.2}$$

Given that there are only slight differences between the predictions of the two equations, and since the two forms are the subject of a later chapter, equation (1.2) will be used for convenience.

The information transmitted, H_t, for error-free performance with N signals of probabilities p_i, $(i=1,2, .., N)$ is given by the equation

$$H_t = \sum_{1}^{N} p_i Log(p_i) \tag{1.3}$$

which simplifies to $Log(N)$ if all N are equiprobable. Thus the logarithmic relationship between RT and N is equivalent to a linear relationship between RT and H_t, i.e.

$$RT = a + b.H_t \tag{1.4}$$

Hick therefore suggested that the "rate of gain of information is, on the average, constant with respect to time." Hyman (1953) has shown experimentally that average RT is affected approximately as expected under equation (1.4) if the stimuli occur with different probabilities, or if errors are made.

Hick (1952a) presented several models of the choice reaction process based on this relationship and modern choice reaction modelling dates from that time. A common approach inspired by information theory has been to consider the human organism as analogous to a communications system or channel through which the stimulus as the input message or signal is transformed into the output, or response. Ongoing unrelated or background neural activity affects the signal and degrades it so that the subject can only process imperfect evidence. These fluctuations in the system, usually assumed to be random and normally distributed, are collectively called "noise". The unreliability they introduce explains at least some of the errors a subject makes.

A wealth of evidence gathered since 1952 has shown most clearly that RT is proportional to the logarithm of the number of equiprobable alternatives. (See reviews in Welford 1968 and E.E. Smith 1968). The slope, B, in equation (1.2) has psychological meaning in that its reciprocal, $C = {}^{1}/B$, varies with the naturalness or compatibility of the stimulus-response *(S-R)* associations in the particular task, while in communication theory, C represents the channel capacity, i.e. the transmission rate, the number of units of information that can be transmitted per time period. Taking logarithms to the base 2 and time in seconds, C is measured in bits per sec. In a true communications channel this value is constant and cannot be exceeded, while for human choice RT tasks it varies over a wide range, depending as it does on B. Thus care should be taken in applying this concept to human systems and perhaps a better term would be channel usage which avoids the assumption of an upper limit to the information transmission rate. However the term channel capacity is in common usage and will be used in this thesis, having noted this caveat.

A less natural association between the stimuli and the responses is reflected in an increase in B, i.e. the number of choices has more effect on RT, and the rate of information transmission, C, decreases. Conversely, as the S-R association becomes more direct, B decreases. Phrased in this way, compatibility is a descriptive concept, not explanatory, for one cannot use it to explain the parameter, B, it is measured by, although it is possible to predict the relative order of C in a set of related tasks by appealing to the concept of naturalness of the relationship between the stimuli and their responses (Brainard, Irby, Fitts & Alluisi 1962), but other factors are involved such as relationships within the response set and the stimulus set and between the S-R associations for different stimuli in the task. In this chapter, therefore, "compatibility" will be used in a descriptive sense only.

1.2 *High compatibility*

It is a point of contention whether *B* can ever be zero, i.e. whether the stimuli and responses can be so highly compatible that RT is unaffected by the number of alternatives. Many models of choice reaction processes predict an unavoidable increase in RT with increasing *N* and cannot be applied as they stand to any situation in which this increase does not occur. Additionally, such a situation represents a case in which the information transmission rate is infinite, implying an unlimited channel capacity. This seems intuitively implausible and, if the results are supported, suggests that information theory is of little value in explaining the underlying processes of choice reaction. Kornblum (1968) and Laming (1968) have both presented other arguments pointing out its inadequacies and rejected it as having no explanatory value. Nevertheless, the mathematical measure of information may provide a valuable metric in some circumstances.

A large number of studies using a variety of stimuli and responses have found that *B* was zero. For example, naming latencies have been shown to be independent of the number of stimulus alternatives for vocal response to digits (Forrin, Kumler & Morin 1966, reviewed in Teichner & Krebs 1974; Theios 1973), and to letters (Morin, Konick, Troxell & McPherson 1965; Waugh & Anders 1973), to familiar words (Pierce & Kashin 1957; Conrad 1962), and to syllables (Davis, Moray & Treisman 1961). Mowbray and Rhoades (1959) gave subjects extensive practice (3600 trials) on choice tasks (up to $N = 10$) and reported that RT was ultimately independent of *N*. In that study, the standard key press response was used with stimulus lights set out in the same spatial pattern as the keys. Mowbray (1960) used different groups of subjects for each degree of choice and still found that the mean RTs were highly comparable for all groups. However, as will be mentioned later, each of these studies is open to criticism by one or more ad hoc explanations, although no one criticism is adequate to reject the results of all the studies.

The study which perhaps provides the example most resistant to explanation in terms other than truly equal RTs for all degrees of choice is that of Leonard (1959). The alternative explanations proposed for the various studies showing no increase of RT with degree of choice will be discussed in the framework of this experiment. Leonard's novel apparatus used response keys which could be set vibrating. The subjects rested their fingers on the keys and were instructed to press whichever key vibrated, as quickly as possible. He found that after less than 500 trials on this vibrotactile (VT) task, mean RTs were equal for 2, 4 and 8 choices (about 225 msec) although simple reactions were faster (about 180 msec). That is, it appears that this is a highly compatible task in which increasing the degree of choice is not reflected in an increase in RT. While this experiment represents prima facie evidence for this conclusion, it is not unequivocal. Given the importance of such a conclusion it is necessary to consider all possible explanations. Five candidates are listed here, four suggesting that some feature of the experiment hid a slight increase in RT with N, and the fifth accepting that Leonard's conclusion was correct.

(1) Only one response measured.

The criticism most directly applicable to this study is that only reaction times from the one finger common to all conditions were measured, although different numbers on fingers were used in different conditions. This was also the case with Mowbray and Rhoades (1959). Had the subjects adopted a serial search strategy in which the stimulus corresponding to that particular response was checked first, then no change in RT would have been measured (Welford 1968). One fact weakens this suggestion: Hick (1952a) measured the RT only for the two fingers common to all his conditions and still found an increase. However since any increase with Leonard's apparatus would be expected to be slight and more easily obscured, the criticism is pertinent to that study.

(2) Unequal practice.

The number of practice trials Leonard gave his subjects increased with degree of choice - 192 trials were given for the simple reaction and the 2 choice, 320 for 4 and 480 for 8 choice. The intention was that the number of each of the alternative responses would be approximately equal across conditions. Given that practice at a task reduces its RT this procedure would give a greater reduction for the higher degrees of choice, perhaps enough to conceal a small change in RT.

(3) Familiar subsets.

For tasks using numerical stimuli, it has been suggested that subjects are so familiar with the stimuli as a complete set that they will always respond as though faced with a choice between the whole set even if only some are used in a particular trial. Consider the case where the stimuli are the numerals 0-9 or a subset of them. Although the subject is told that either a 4 or a 7 will occur on any trial, i.e. $N = 2$, he reacts as though any of the full set of 10 may occur, and consequently his RT for the nominal 2 choice will be that of the 10 choice. He will do so, presumably, because daily practice with the complete set of numerals had made it difficult to ignore those possibilities not in the task. This would hold for unfamiliar subsets like 4 and 7, but might not do so for familiar ones like 1 and 2, which should show RTs shorter than for the full set. Fitts and Switzer (1962) found this to be so in an experiment designed to test such a possibility.

While this view may be defensible for overlearnt stimulus sets in such tasks as reading letters or digits, it is less probable for VT stimuli on two counts. Firstly, the RTs seem to be too fast to be treated as 8 choice RTs when compared with other key response tasks. Evidence from a stimulus detection task (Smith 1977), which showed that RT in RT choice tasks is at a minimum determined by response factors and not degree of choice will be discussed in detail later. Secondly, even if subjects do treat the task as 8 choice for all *N*, the question remains as to why this is not the case in other logically quite similar tasks, particularly when the stimuli and responses are determined by their spatial location as they are in *VT* tasks. A particularly strong example showing the persistence of RT's dependence on the number of alternatives defined (irrelevantly) by their spatial location, is given in an experiment by Teichner and Krebs (1974). Subjects were required to make the same response regardless of which light came on, with N = 1, 3 or 6. Although the same response was required to all the different lights, mean RT still increased with the number of stimuli, albeit only slightly. Thus, the familiar subsets argument appears to be inappropriate for key press tasks and may be discounted.

(4) Increase hidden by a minimum response time.

If through any case subjects cannot respond faster than some minimum time in a key pressing choice task and if the processing time for up to say 8 VT stimuli is less than this time, no increase in RT may be found for N less than 8. That is, even if the processing time does depend on N, it would be expected that an RT "floor effect" could hide it up to some degree of choice. Beyond this the increase would become apparent in the measured RT.

An example where such an explanation holds was given by Crossman (1953). His subjects held a pack of playing cards face down in the hand and, turning them over one at a time, sorted cards into various classes, ranging from $N = 2$ (Red versus Black) to $N = 26$ (the 13 red and 13 black numbers). The time taken to sort rose approximately with $log\ N$ from a basic movement time. The latter was measured by sorting a pack of cards prepared in a prearranged sequence so that the time taken consisted only of the time required to turn the cards over and place them into piles within any requirement of making choices. When, however, the subjects were given a shuffled pack, face up, to sort into piles the response time per card was approximately either $k.Log(N)$ or the movement time, whichever was longer. With the pack face up subjects could see and start processing the next card while moving the current card to its pile, but the RT could never be less than the movement time which produced a floor effect. If something similar holds within a trial with VT stimuli, this minimum time will cover the increase in processing time in a fashion analogous to movement time in Crossman's study.

Of course, showing that RT is at a minimum in a VT choice task does not imply that there is an increase in processing time with N. There may not be, in which case RT would be independent of N for all N. That is, the difference between the hypotheses that $B = 0$ and $B > 0$, each masked by a minimum response time, appears at some higher degree of choice, where $B > 0$ implies that RT will increase for N above some critical value, while $B = 0$ implies that RT will be equal for all N.

(5) <u>No increase in processing time.</u>

This hypothesis accepts the prima facie conclusion that for some reason VT stimuli with corresponding key press responses represent a limiting condition in compatibility in which processing time is actually independent of N. The cause or origin of such high compatibility may be innate or acquired. Part of the answer may lie in the fact that there is close spatial contiguity at the spinal level of the receptor-CNS-effector chain for these stimuli and responses, as Moray (1969 p.117) has noted, in that each pair project through the same segmental level.

Obviously it is this last hypothesis which poses difficulties for modelling, representing as it does an infinite rate of gain of information which is at variance with ideas about people as information processors of limited capacity. This argument is only as strong as the evidence on which it is based, and the alternatives (1)-(4) need to be investigated. E.E. Smith (1968) noted that Leonard's result had not been successfully replicated and concluded that "the evidence for obtaining no relation between CRT and *N* in a highly compatible task is weak." The experiment reported in this chapter is an attempt to gain further evidence on this point.

We appear to be left with hypotheses (4) and (5) as the main possibilities. The experiment reported here was designed to distinguish between these and to provide confirmatory evidence regarding the others.

2. EXPERIMENT 1

2.1 Introduction

The author has reported elsewhere an experiment using a VT task in which 2, 4 and 8 choice mean reaction times were not significantly different for compatible responses when comparisons were between the same fingers across degrees of choice (Smith 1977). However, that study does not unequivocally allow the conclusion that 2, 4 and 8 choice RT were equally fast, again for two reasons.

Firstly, there was a significant difference in the direction of 2 faster than 4 faster than 8 choice for RT taken over all fingers with the mean RTs being 223, 239 and 246 msec respectively. Nevertheless these differences were most likely an artifact of observed differences in the strengths of the stimuli. This was tested, using a series of trials the responses for which were to be made in a set sequence, regardless of the stimulus order. Hence the subject knew in advance which response was to be made at the onset of the next (random) stimulus. Stimulus identification was thus not needed at all, only detection of its onset. With each response made equally often to each stimulus in the predetermined response sequence, comparisons between the detection times for each stimulus (seen as a measure of stimulus strength) and between the response execution times for the 8 fingers were possible. This showed that one of the stimuli common to all *N* was the strongest (i.e. had the shortest detection time) while one used only in the 8 choice was the weakest. It was therefore argued that the 8 choice RT was artificially increased and the 2 choice decreased.

Secondly, the subjects were given a block of 196 trials of the 8 choice task before they did a block of each of 2, 4, and 8 choice, in counterbalanced order. This was a necessary part of the procedure as in other sessions non-compatible stimulus-response pairings were used and a check was needed as to whether the subjects understood the pairings correctly. These preliminary trials introduced the possibility that the subjects were responding in all blocks as though their choice set had all 8 stimuli. This possibility was noted by Leonard (1959) in relation to his experiment. In the present experiment this was probably not the case, since the lack of increase of RT with degree of choice held only for the compatible task, and not for the others. A stronger argument is that subjects did not respond any faster in the task mentioned above which needed only stimulus detection. Indeed, a finger by finger comparison between the 8 choice RT and the average of the stimulus detection and response execution times calculated from the detection task showed these to be highly similar as shown in Figure 1.1 - the maximum difference was 15 msec. That is, subjects were equally fast whether they made a response determined before the stimulus was given or made the response directly determined by the stimulus. This also suggests strongly that subjects were at some minimal level of RT and therefore were not treating all conditions as though *N* was 8 (both possibilities mentioned by Leonard 1959), or else this would surely have been slower than the 8 stimulus detection task.

If it can be shown convincingly that RT in this key-response task can be independent of *N*, then such results have important implications for models of CRT processes for the following reason. If we consider the choice process in finer detail, and accept its division into 4 substages:

(1) stimulus preprocessing,
(2) stimulus categorization,
(3) response selection,
and (4) response execution

as E.E. Smith (1968) does, two possible conclusions follow logically. Firstly, if the stages do not overlap in time, i.e. one must finish before the next can start, and the total RT is the sum of the component times, then either none of the stages is influenced by *N* in the *VT* situation - which is the generally accepted view - or two or more stages are mutually compensatory, i.e. one stage's time increases with *N* but this is matched exactly by a decrease with *N* in another stage. The latter seems unlikely. The consequences of no overlap and independence with *N* can be extended when considered together with the results of the stimulus detection

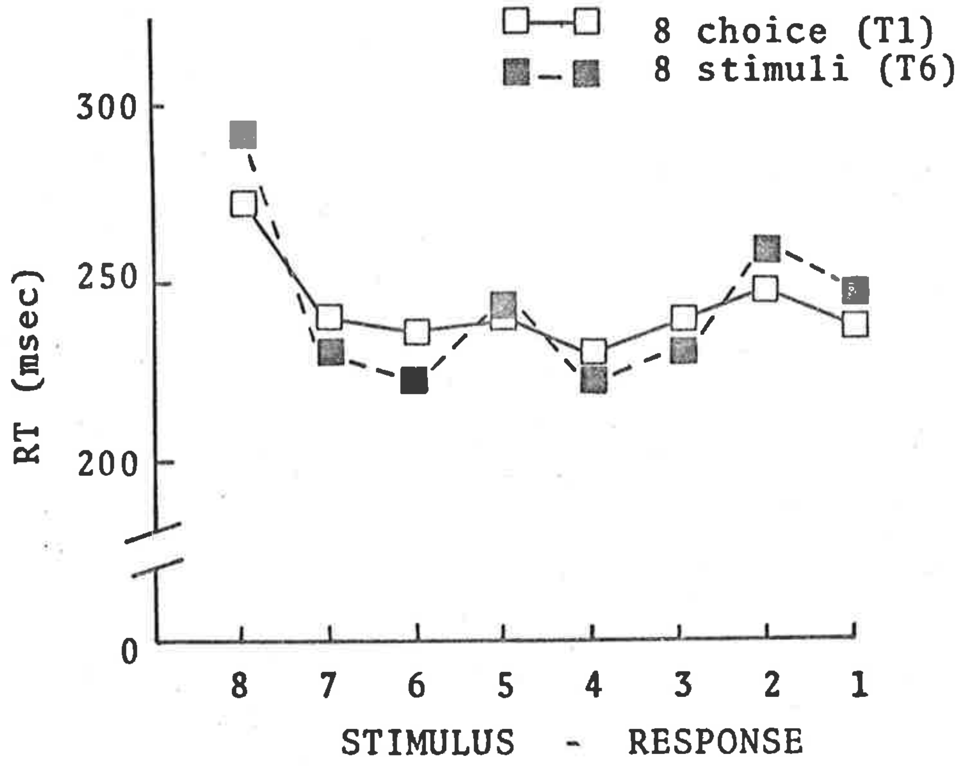

FIGURE 1.1: Comparison of eight-choice mean RTs for the compatible S-R association with the mean of the stimulus and response profiles from the eight stimulus detection task. (From Smith 1977).

task mentioned above (Smith 1977). In this choice RT task the two stages, stimulus categorization and response selection would seem not only to be independent of *N* but also very short. Comparing the two tasks under additivity assumptions implies that these two stages, not present in the detection task, together take an amount of time equal to the sum of all four stage times minus the times for stages (1) and (4):- i.e. the difference between the RTs of the two tasks, 8 choice response and 8 stimulus detection. This was found to be not significantly different from zero. Considered in this way, the independence of all stages with *N* is in keeping with RT being at a minimum level.

There is however an alternative. The stages may overlap in time to some extent, i.e. one stage can start processing incomplete information from the previous one. For example, partial stimulus categorization could be processed by the response selection stage as it is produced. The possibilities under such overlap assumptions are many and complex as Taylor (1976) has shown. One possibility is that only one stage in the above breakdown is affected by *N*, e.g. response selection but it is so rapid that it can be overlapped completely by its adjacent stages. Consideration of this approach together with the stimulus detection results would suggest that both stimulus categorization and response selection were swamped by the other two stages even for an 8 stimulus task since removing the need for these stages and requiring only stimulus detection and response execution did not decrease RT.

The above argument concerning stage overlap when the processing time is affected by *N* parallels hypothesis (4), the floor effect. Stage overlap is also possible if processing time is unaffected by N, so that concluding that RT is independent of N gives no indication as to whether or not the stages overlap. The experiment now to be reported was intended as a replication of that by Leonard (1959) free of the possible criticisms attaching to his.

2.2 *Method*

Apparatus.

The apparatus was that used by Smith (1977), i.e. a set of 8 keys arranged in 2 arcs of 4 in such positions as to allow the subjects to rest one finger (excluding the thumbs) comfortably on each key. The keys were 13 mm in diameter, dished at the top to fit fingertips. A force of about 150 gms was needed to activate a microswitch linked to each key. Vertically through the centre of each key was a rod, 3 mm diameter, which could be vibrated up and down at 100 c/sec independently of the rest of the key. This vibration acted as the stimulus. The rods were adjusted so that their resonant amplitudes were approximately equal. In doing this, the inequalities in stimulus strengths noted in the author's previous experiment (Smith 1977) were minimized. A faint buzzing, coincident with the vibrating stimulus was unavoidable with this design for the VT keys. This was considered to be too soft to influence the results in any significant way since the hearing of sound attenuators had no effect on measured RTs with this apparatus (Smith 1973).

The presentation of stimuli, recording of all responses and response latencies were controlled by a PDP-8 computer in an adjacent room. The stimulus onset was always with the up phase of a vibration cycle and remained on until a response, correct or not, was made. The time between trials, (*RSI*), was measured from the release of the key pressed to the onset of the next stimulus.

Subjects.

Six male and six female subjects were used, none of whom had previously participated in reaction time experiments, and all of whom were naive as to the purpose of the experiment. They were unpaid volunteers, undergraduates at Adelaide University not studying psychology.

Procedure.

Each subject came for two sessions on different days about 7 days apart. On day 1 the subject was given 48 trials to familiarize him with the stimuli and responses to be used. In these trials the subject was told that the stimuli would come in a set order, the first would be the rightmost one (little finger, right hand), the second would be the one adjacent to its left (ring finger, right hand), and so on across the eight stimuli, so that the eighth stimulus was to the little finger of the left hand. This sequence was presented 6 times with a constant *RSI* of 2 seconds. Subjects were told to respond by pressing the key which vibrated, without hurrying. Thus each subject was familiarized with the apparatus in the task without the stimulus and response uncertainty of the choice task.

The experiment proper then began. Each subject did 4 blocks of 192 trials preceded by 4 warm-up trials which were excluded from the analysis, one block for each of the degrees of choice, 1, 2, 4 and 8 choices. The stimuli and responses used for each degree of choice were: *N = 1*, the right index finger; *N = 2*, both index fingers; *N = 4*, the index and middle fingers of both hands, and all 8 for *N = 8*. In all cases, all 8 fingers were kept in position on their keys to keep response production factors comparable. In each block, each stimulus occurred an equal number of times in each 24 trials. *RSI* was varied randomly between 1 and 2 seconds. The order in which subjects were given the four degrees of choice was determined by a Latin square. Subjects were told that as soon as they felt a key start to vibrate, they were to press down that key. They were also told how many and which stimuli would occur in that block.

The procedure on day 2 was the same as that on day 1 but without the familiarization trials.

2.3 *Results and Discussion*

TABLE 1.1: *The first four columns give the mean correct RTs (msec) and 95% confidence intervals for each degree of choice. Each mean is calculated from 2304 trials, less errors, i.e. 192 trials for 12 subjects. The results obtained by Leonard (1959) are given for comparison. The last column gives the slop, B (msec/bit) and 95% confidence interval from the equation* $RT = A + B.\log_2 N$ *which best fits the data for N = 2,4 and 8.*

	Degree of choice, N.				
	1	2	4	8	slope (B)
Day 1	190 ± 18	236 ± 19	249 ± 25	256 ± 19	10.0 ± 15
Day 2	181 ± 19	212 ± 16	203 ± 18	216 ± 14	1.7 ± 11
Leonard	182	226	229	217	

Mean correct RTs for each subject and each condition on Day 1 and Day 2 are given in Appendix 1. All subjects responded with less than 4% errors, and the mean error rates were 0%, 1.2%, 1.2% and 1.0% for the 1, 2, 4 and 8 choice respectively. Error trials were thus too few for meaningful analysis. Mean correct RTs were calculated for each N over all subjects. Table 1.1 presents these means and their 95% confidence intervals for Day 1 and Day 2, together with the corresponding means from Leonard (1959) for comparison. Latin square analysis of variance (Winer 1962, p.539) with all 4 levels of N for Day 2 showed that only N and Order by N interaction were significant at $\alpha = 0.05$. (The analysis table is given in full in Appendix 1). Three orthogonal planned comparisons were calculated, namely $N = 1$ with the rest, $N = 2$ with $N = 4$, and $N = 8$ with $N = 2$ *and* 4. The results were $t_{24} = 5.49$, 1.21 and 1.90 respectively. Only the first is significant at $\alpha = 0.05$. This confirms Leonard's conclusions that simple RT was faster than 2, 4 and 8 choice, with no increase in RT after $N = 2$.

The significant Order by N interaction was probed further. Four orders were used, $a = (1,2,4 \text{ then } 8)$, $b = (8,4,2,1)$, $c = (4,8,1,2)$, and $d = (2,1,8,4)$. Looking at the reaction times for each order by N combination, it was noticeable that a and b were faster than c and d for $N = 1$ and 4 by about 20 msec, while the other differences were all smaller than 7 msec. The significant interaction is attributable to this. Checking the sequential position shows that $N = 1$ and 4 occurred first and third in a and fourth and second in b. No ready explanation for this effect is apparent and the experimenter feels that it is not replicable. No meaning is therefore attached to this interaction.

The final column of Table 1.1 gives the slope, *B* and its 95% confidence intervals for the linear regression of RT with log_2N, calculated from individual subject's means for N = 2, 4 and 8 for each day. The simple reaction, N = 1, was not included in this analysis as it clearly lies below the best fitting line through the choice RTs. Leonard (1959) suggested several explanations of this for VT situations. These were investigated and will be discussed in Chapter III.

TABLE 1.2: Mean and corresponding 95% confidence interval for individual finger's RTs (msec) for each degree of choice are listed for day 1 and day 2.

	STIMULUS							
N	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Day 1								
1					*190±23*			
2				*251±27*	*219±25*			
4			*253±30*	*261±34*	*231±31*	*246±31*		
8	*256±29*	*274±26*	*248±26*	*260±29*	*230±33*	*245±25*	*278±27*	*254±23*
Day 2								
1					*181±21*			
2				*218±18*	*205±18*			
4			*209±24*	*193±21*	*203±20*	*210±24*		
8	*225±25*	*227±26*	*216±27*	*205±22*	*208±24*	*210±25*	*227±27*	*219±18*

Leonard (1959) measured only the RT of one stimulus in each task, which may be contaminated by a strategy bias as noted in explanation (1) above. In this experiment RT for fingers in each task were measured and these are given in Table 1.2 together with their 95% confidence intervals. Had only the RTs of the stimulus 5 been measured as it was the one common to all tasks, it can be seen that there would not have been any significant difference between the various degrees of choice, after only 192 trials on each. Indeed, comparison of the RTs of the 4 choice stimuli with the corresponding data from the 8 choice shows a striking similarity, with a maximum difference of 5 msec and the 2 choice RTs are parallel but about 10 msec faster on corresponding fingers. Three of the 4 fingers unique to the 8 choice are the slowest over all *N* while the fourth is exceeded by only one other. This makes the 8 choice overall RT greater than the 4 choice, and could be the result of a strategy of checking the inner 4 stimuli first or because these inner responses have been made more frequently.

On Day 2, fingerwise comparisons across *N* again show very little difference, but the fingers unique to the 8 choice are now not so much slower and the overall means are no longer significantly different. So the argument in (1) is not without foundation as a criticism of Leonard's results, but this experiment shows it to be inadequate and that it can be rejected. It is certainly true that comparison of the overall means is the more conservative approach.

Explanation (2), which suggested that Leonard's results arose from giving more trials on higher degrees of choice is found not to be an effective criticism since this experiment gave the same result using equal numbers of trials for all degrees of choice.

Consideration of explanation (4), i.e. an actual increase in processing time hidden by some minimum response time, is less clearcut. It cannot be rejected utterly, but the following argument suggests that it is not correct. Inherent in this idea is the suggestion that RT would increase with N once processing time was longer than the minimal level. The effect of practice in decreasing RT may give a test of this. At lower levels of practice some increase with N may still be present, but this disappears as the subject gains experience. As practice reduces RT, the first to reach the floor will be the 2 choice, then the 4 and finally the 8 choice. At the intermediate level then, the difference between the 2 and 4 choice RTs will be zero, while the 8 choice will still be slower. That is, the difference between RTs for $N = 2$ and 4 will be less than between $N = 4$ and 8. The overall means for day 1 do not show such a pattern, and indeed the difference between the 2 and 4 choice RTs is 13 msec compared with 7 msec between the 4 and 8 choice RTs. These differences are small, but their magnitudes are in the wrong order for this idea. This result was followed up and, ancitipating the next chapter briefly, was confirmed so that (4) could be rejected.

All of the evidence favours the conclusion that processing time is not affected by the degree of choice in this VT task after one session's practice. From the data presented here, the 95% confidence interval for the slope, B, in equation (1.2), includes zero for both days. Moreover, on day 2 the slope is 1.7 ± 11 msec/bit, acceptably near zero. Nor does it seem feasible that the zero slope arises solely because reaction to tactile stimulation is an almost reflex form of response which in some way bypasses more central neural processing as Broadbent (1971) mooted. If this were the case, one would not expect even the 10 msec/bit increase found on the first session.

The increase in the first session does, however, need explanation. Early in practice, subjects may process extraneous aspects of the situation - for example, the slight buzzing of the vibrating key or the nature of the stimulus sequence. Until they can develop a strategy of disregarding these and attending only to the salient features an increase in RT may occur. Support for this idea can be gleaned from studies which show that subjects do process logically superfluous information, as indicated by longer RTs if such irrelevancies are present. The Teichner and Krebs (1974) study mentioned above is one such. In that study, subjects pressed one key in response to the onset of a stimulus chosen randomly from 1, 3 or 6 visually presented numerals or mirror images of numerals. They found that RT for that one response increased with the number of stimuli, suggesting that subjects were processing information about the numbers although this was not called for in the task. Again, Boulter (1977) found that RTs were longer if the stimulus modality (visual, auditory or tactile) was cued before the trial than if it was not, although all stimuli required the same response. This effect decreased with practice and disappeared after 11 sessions. His interpretation was that subjects can direct their attention to the cued channel, but the data are also consistent with the subjects' processing to determine the modality if it is uncued, although this is irrelevant to the task. The effect of practice in eliminating this extra time is consistent with subjects' developing a strategy which enables them to discard this unwanted processing.

Bernstein, Schurman and Forester (1967) report similarly that a single response to 8 spatially separated lights was faster if the position was cued than if it was not, again suggesting that subjects can ignore the irrelevant feature if they are able to preprocess it, but that otherwise they will process it. That is, their attention can be diverted away from irrelevant processing, but not without either prompting or practice. A similar effect may account for the early increase in RT with *N* found in this experiment.

2.4 Conclusion

Considered overall, it seems that this VT task is very compatible for novice adult subjects and rapidly becomes maximally so. Certainly this experiment reinforces the evidence in favour of hypothesis (5) so that an adequate model must allow choice RT to be unaffected by the number of alternatives although simple RT remains shorter. This poses difficulties for serial additivity models as noted in the introduction.

CHAPTER II

CHILDREN's CHOICE REACTION TIME TO VISUAL AND VIBROTACTILE STIMULI

1.1 Experiment 2

In the previous chapter reaction time was shown to be independent of the number of alternatives and it was argued that the results were consistent with only two of the five hypotheses put forward as explanations. These were:- (4) that a floor effect hid an increase in processing time, or (5) that there was really no change in processing time.

If the former is true, the increase should appear in RT for N greater than the degree of choice (D) for which the processing time exceeds the floor RT level. That is, there will be differences between the RTs for any two Ns greater than D but no differences for Ns less than D. As processing time decreases with practice, so successively higher degrees of choice will reach the floor RT. Consequently the difference between the reaction times for lower degrees of choice will become zero before it will for higher Ns. This hypothesis therefore predicts that $RT_4 - RT_2$ (low Ns) will be less than $RT_8 - RT_4$ (higher Ns) until all reach the floor level and $RT_2 = RT_4 = RT_8$. (In this notation, RT_i stands for the mean reaction time for a choice between i alternatives).

The evidence from the previous chapter suggested that this was not the case:- it was found that $RT_8 - RT_4$, averaged over 12 subjects was 7 msec while $RT_4 - RT_2$ was 13 msec over the first 192 trials. That is, the 4 and 8 choice were more similar than were the 2 and 4 choices, which is the opposite of the prediction above. The differences were, however, small and to that extent the evidence was weak. It was therefore decided to test hypothesis (4) further on this prediction.

1.2 Method

It was felt that the result would be more clearcut if children were used as subjects because it was suspected that novice children would be less practised in spatial location in all modalties than novice adults since much of everyday living experience involves spatial location of various types. The difference of interest was only 6 msec (13-7) for adults in the first 192 trials, and it was hoped that the results for the less practised children would be more definite.

There is evidence to suggest that developmental changes result from systematic changes in relationships between the senses, with proximoceptor systems such as touch being more dominant than teloreceptor such as vision in young children, and vice versa for older children. Kaufman, Belmont, Birch and Zach (1973) used RT paradigms to show that this change is gradual, with vision being dominant at about 6 years and older. The subjects chosen were older than this changeover age so that the relative effectiveness of visual and vibro-tactile senses was comparable with adults. A second constraint was that their hands could comfortably span the keys on the VT apparatus used.

As a control, a visual 2, 4 and 8 choice task was run to check whether any feature of the results was an artifact of child-adult differences beyond experience factors and to ensure that the children's results could be considered as "underpractised adults".

Subjects.

Twenty-four children between the ages of eight years and eight years eleven months from a Year 4 class at a suburban primary school acted as subjects in this experiment. Twelve were female and twelve were male. All could comfortably span the keyboard of the apparatus.

Apparatus.

The vibrotactile apparatus described in Chapter I was used for both stimuli and responses in the VT task. The subject sat at a table which carried the keyboard. Both chair and table were the appropriate size for 8 year olds.

For the visual choice task, the stimulus display was a horizontal row of 8 lens-topped neon bulbs, 16 mm diameter with intercentre distance 22 mm, mounted in a 20 cm square black surround. Between the central lights there was a vertical grey line. This display was placed at eye level on a table 2.5 m from the subject's chair. The VT keyboard, with the vibrating rods deactivated, was used for the 8 response keys. Thus response production factors were identical for the two types of task.

Procedure.

Half of the subjects, 6 male and 6 female, did the task with VT stimuli and half with visual stimuli. Each subject did all three conditions, N = 2, 4 and 8, with order counterbalanced across subjects. Each condition consisted of 20 practice trials which were not included in the analysis, and were followed by 128 trials, with a response-stimulus interval (*RSI*) of 1 second. An equal number of each stimulus occurred in each 64 trials.

In addition, the N x N possible pairs of stimuli were equally represented in the pairs of stimuli given on successive trials in the two halves to balance sequential effects. That is, for each particular stimulus, the stimulus on the trials preceding its occurrences were equally divided between the members of the stimulus set. However this feature was irrelevant for the purpose of this study and results relating to it were not analysed here.

At the start of the session, the stimulus-response association, direct spatial compatibility, was described to each subject in detail by showing which response was correct for each stimulus. They were told to press the correct button as soon as they felt (or saw) the stimulus and to go as fast as they could while not making many errors. No subject had any difficulty in understanding the task.

At the school's request, subjects were run in pairs, so that one subject watched while the other did the 2, 4 and 8 choice conditions of the task. They then changed roles. The experiment was run in a spare classroom adjacent to the children's own room. These two points lessened any anxiety which the children might otherwise have experienced. A PDP/8 computer controlled the presentation of stimuli and the recording of response details.

1.3 Results and Discussion

The individuals' mean correct RT, with standard deviations and error percentages are given in Appendix 2. The RT data are summarized in Figure 2.1 which shows the mean RT for each task and condition, separately for males and females. Table 2.1 gives the mean correct RT and error percentages for each task and condition. Errors were too few for reasonable analysis.

TABLE 2.1: Descriptive statistics for the two tasks (VT or visual stimuli) in Experiment 2. Data are from 12 subjects in each task, based on 128 trials under 2, 4 and 8 choice conditions for each subject.

		N		
	Task	*2*	*4*	*8*
	mean correct RT (msec)	*516*	*569*	*564*
VT	*standard error*	*43*	*48*	*38*
	median % errors	*6.6*	*6.3*	*4.7*
	mean correct RT	*554*	*796*	*1042*
Visual	*standard error*	*25*	*35*	*62*
	median % errors	*3.5*	*5.9*	*9.9*

For the VT task, the 4 and 8 choice conditions' overall mean RT were nearly equal (569 msec and 564 msec respectively) while the 2 choice is shorter (516 msec). That is, $RT_8 - RT_4$ is less than $RT_4 - RT_2$, which is contradictory to the prediction of hypothesis (4) and it can therefore be rejected. A related sample t-test between $RT_4 - RT_2$ and $RT_8 - RT_4$ gave $t_{11} = 3.04$, $p < .02$, 2-tailed, in the direction expected on the basis of Experiment 1, against hypothesis (4). This means that an increasing processing (hidden by a floor RT) does not underly the lack of increase in RT with *N* found in day 2 in experiment 1. An analysis of variance (*N* by order by sex) showed no significant effect of *N* on the mean correct RTs. Nor were the sex differences significant, as shown in the analysis table in Appendix 2.

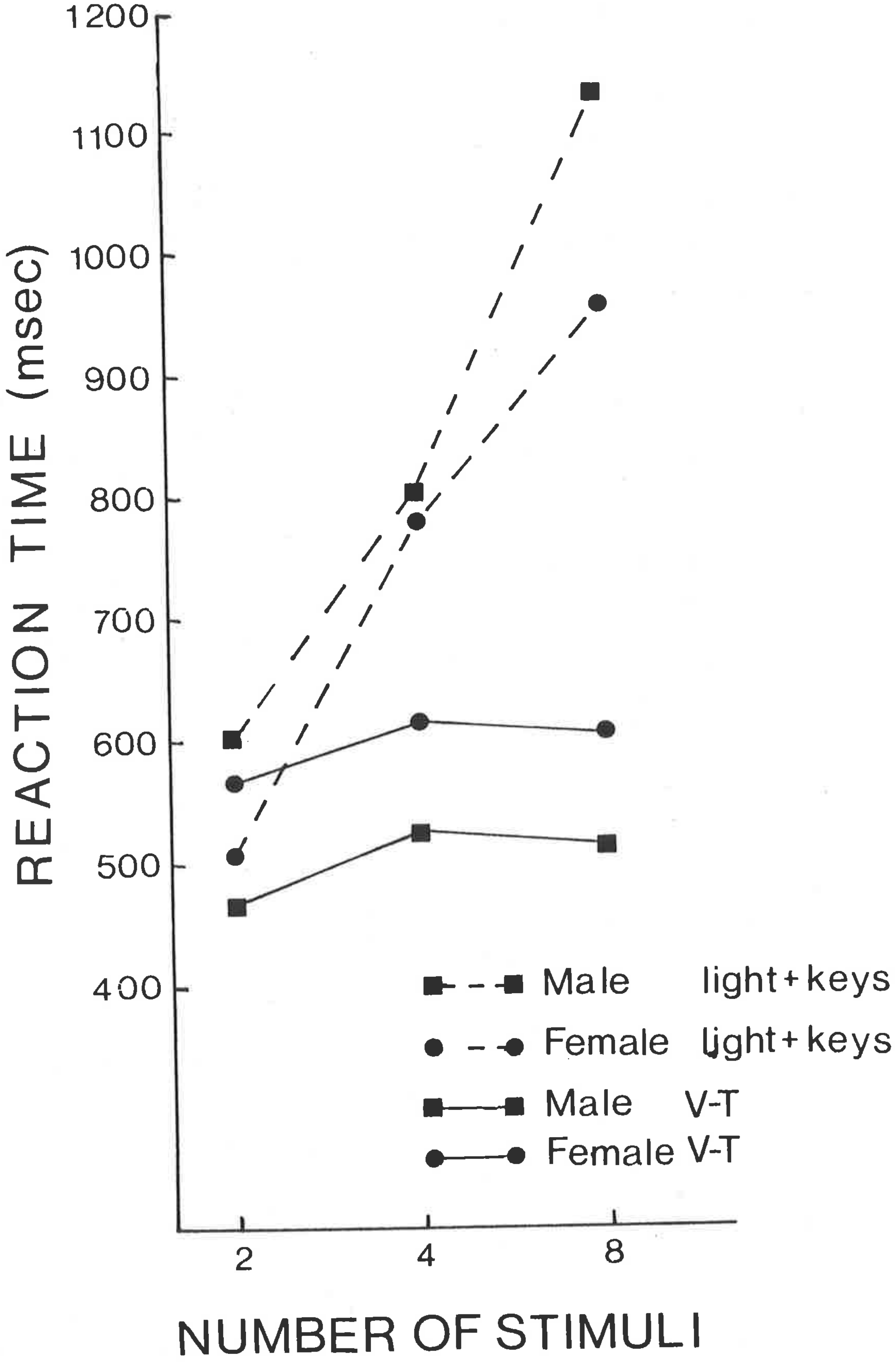

FIGURE 2.1: Choice reaction times for 8 year old boys (squares) and girls (circles) responding to 2, 4 or 8 VT or visual stimuli. The stimulus type by number of stimuli interaction is significant (p = .0003).

The results for the visual task were as expected on the basis of considering children as underpractised adults. That is, RT was linear with $log(N)$ and the slope was greater than for adults. This was shown by fitting the regression equation (1.2), RT = $A + B.log_2(N)$, to the data. This equation accounted for 84% of the variance (a correlation of .92) with A = 310 msec and B = 244 msec/bit. This corresponds to a rate of information transmission or compatibility, C = 7.3 bits/sec (calculated from Welford 1971, experiments 1 and 3). That is, both A and B are less for adults than for children. Taken with the conclusion of Teichner and Krebs' (1974) review of visual reaction tasks, that practice reduces A and B, this suggests that children in this choice task do indeed act like underpractised adults. There seems no reason to suggest that this does not hold for the VT task also, especially since the pattern of $RT_8 - RT_4$ and $RT_4 - RT_2$ found here in the VT task was similar to that for the adults on day 1 as reported in Chapter I.

So the main conclusion of this experiment is that the data are against an increase in processing time being partially hidden by a floor effect. This leaves one explanation of why RT is independent of N in VT tasks; to wit, N does not affect any part of the RT processing for this highly compatible situation.

CHAPTER III

THE EFFECTIVENESS OF A DISCRETE STAGE APPROACH TO RT

1\. Early in the study of reaction time Donders (1868, see Koster 1969) proposed a theory and method for investigating the structure of the RT process. He suggested that a choice reaction (Donders' *b* type) was composed of a series of sub-processes or stages each starting only after the previous one had finished. That is, the overall RT could be split into discrete amounts, each attributable solely to one of a succession of non-overlapping stages. In his review of choice RT, E.E. Smith (1968) suggested that the following four stages are present in a choice or *b* reaction:

(1) stimulus preprocessing

(2) stimulus categorization

(3) response selection

and (4) response execution.

For consistency the following discussion will be in terms of these stages. To investigate these stages, Donders used a set of three RT tasks differing as to which of the stages were assumed to be involved. The task in which all stages were present was the choice reaction consisting of several stimuli each with its own response to be made whenever it occurred. A selective or *c* reaction, which requires a single response to one of several stimuli and nothing to the others, Donders suggested, lacked a response selection stage but contained all others from *b*. In a simple or *a* reaction, a further stage, stimulus identification is absent. In this discussion, to distinguish between the task and its RT, italicised letters will be used to denote the task and uppercase for its RT. Under Donders' subtractive principle, the duration of stage (3), response selection, can be obtained by subtracting C from B, since *b* and *c* are differentiated only by its presence in *b* and absence in *c*. Similarly the stage time for stimulus identification is given by C - A.

In this framework, there is a qualitative difference between *a*, *b* and *c*. Other workers of the time did not accept this. Kulpë argued that the difference could be quantitative, noting that greater response preparedness was possible in a simple response than if a choice was called for. That is subjects can set their motor readiness to a higher level when only one response is needed (*a* and *c*) than if several are possible (*b*) and higher still if that response can be executed as soon as any stimulation arises (Woodworth 1938). Martius (1891, see Henmon 1914,p.29), noting that RT is shorter if the subject's attention is directed to responding, than if attention is to the stimulus, argued similarly: with a plurality of possible stimuli and responses, it is not possible to preprime a response as fully as can be done in *a*. Further, Wundt (1883) held that the difference between *c* and *b* is not the presence of stage (3), since *c* involves not only stimulus identification but also a choice between movement and no movement. Cattell agreed and further felt that stages (2) and (3) were processed in parallel: as the nervous impulse from the stimulus excitation reached the brain it caused effects in two directions, one to a centre for perception, and the other to the muscle via a motor centre (Henmon 1914,p.9).

The stage approach provides a fair integration of many results on RT processing, and is intuitively attractive. Each stage can readily be understood as representing a particular aspect of RT processing and the effect of various factors on RT can be interpreted readily and logically by reference to their effect on one or more of the hypothetical stages (as reviewed by Sanders 1977). Studies of perception with backward masking suggest that, to form an adequate impression of the stimulus, it needs to be presented for an appreciable though brief period - certainly for much shorter than a full RT - and the minimum adequate duration (Kahneman 1968, Vickers, Nettelbeck & Willson 1972) can be considered as measuring a stimulus preprocessing stage. Subjects usually become aware of the stimulus identity during processing and so a stimulus identification stage is plausible. They also make one response from all those possible, which suggests a response selection stage. The production of this selected response can be delayed under instructions until some subsequent signal, so a separate response execution stage can be created.

Other attributes of stages, especially their sequencing and seriality (order and non-overlapping) are more open to criticism. For example, whether stimulus identification takes place before response selection, as stage theories postulate, or in parallel, as Cattell suggested, is debatable. Both have found support: Coltheart (1972) put forward a model of word recognition in which the visual encoding and the naming process begin at the same point in time and Wood (1974) found results consistent with parallel processing of auditory and phonetic information in speech perception, while Sternberg (1969) supported a serial approach which will be discussed below. Although in most choice RT tasks, subjects' introspective reports suggest that stimulus identification is available to them before the identity of the response, this is not the case for vibrotactile (VT) tasks. Under conditions of spatial compatibility with VT stimuli subjects frequently say that they identified the stimulus at the same time as or after responding, which could imply parallel processing of stimulus identification and response selection. Although it cannot be shown that conscious recognition is equivalent to the end of processing the stimulus, it may be accepted as a working hypothesis for some interesting but tentative theoretical explanations. One may then speculate that the stimulus identity conceptually may itself be a "response", selected in parallel with the overt reaction. Usually stimulus identification, being highly compatible, is faster than other response selection and so appears to occur first; but in VT tasks, the two are about equally fast. If so, it is in highly compatible tasks that evidence in favour of parallel processing could be found.

Sternberg (1969) revived a modified and improved methodology to investigate stages of RT. He started by assuming that non-overlapping stages exist, each ideally having four properties - (1) for a given input, the output is unaffected by factors influencing its duration, (2) a stage should be functionally interesting,psychologically, and qualitatively different from other stages, (3) one stage can process only one signal at a time, and (4) stage durations should be stochastically independent. To discover such stages using Sternberg's method is conceptually simple. Given two factors (experimental variables) which individually influence choice RT, then if their joint effect on RT is additive, they affect different stages, but if they interact they influence at least one stage in common. This can be extended logically to more than 2 factors, and the patterns of interactive or additive joint effects determine the stage structure of the task. Starting with a set of M mutually additive factors, indicating M stages, a new factor which is additive with all M factors defines a new stage, and the nature of the factor gives insight into the functional nature of the new stage. This approach is called Sternberg's additive factor method.

However no a priori reason is offered for the existence of stages - Stone (1976,p.297) refers to Sternberg's "presumption" of stages - although the approach has merit on the grounds that it is comprehensible and parsimonious. Nevertheless, the mathematics of the approach do not dictate or rely on the existence of stages. If factors are additive it may be inferred that they are affecting different, additive, parameters of the process, and if they interact an effect on a common parameter is likely, but to jump from this to the identification of parameters as discrete stages is not trivial. The alternative approach can be called the parameter approach, and has the advantage that it avoids the drawback of discrepant results from closely related studies. For a discussion of such sets of studies see Blackman (1975), Pachella (1974), and Stanovich and Pachella (1977). Pachella (1974) reviewed a broad area of RT experiments, concluding against stage approaches and advocating the careful study of RT per se, which is essentially similar to the parameter approach discussed here. (He also noted that current models are poor if assessed on the criterion of being close analogies to actual events in processing). Such results need a complex series of little stages under a stage approach, but under a parameter approach can be seen simply as implying the existence of a parameter, controlled by differences in the task, which interacts with at least one parameter affected by the other factors in the study. At this stage such a model is little more than descriptive, although a first approximation to such a model will be developed in the next chapter.

Taylor (1976) also strongly criticised the additive factor method and put forward a viable alternative. He suggested that stages may overlap to a greater or lesser degree, even to the extent of being fully parallel. He developedthese alternatives thoroughly in psychological and rigorous mathematical terms, and advocated a more sophisticated but related analysis to probe the attributes of his redefined stages. As his meaning of "stages" eliminates the traditional concepts of seriality, stage independence and stochastic independence, a new term, "component" will be used for a Taylor-type stage. This leaves "stage" for the traditional Sternbergian idea. Since a component may start processing partial information from a previous component, the idea is more like a flow of information through the overall RT process. The difference can be seen in a bead-threading analogy. To thread a set of beads (stages) onto a cord under the stage approach, the needle must be passed completely through each bead before the next is tackled,while with a component approach, a second bead can be started on the needle before it is fully out of the previous one. This provides a less restricted outlook on RT processing.

Evidence of component overlap has been recently reported by Stanovich and Pachella (1977). Their experiment used the additive factors methodology to probe the stimulus categorisation stage, via the factors of stimulus probability, stimulus contrast and *S-R* compatibility. Over a series of experiments they showed that stimulus contract and *S-R* compatibility interacted under-additively where this is defined as occurring "when a factor that slows processing has a larger effect on the faster levels of the other variable". This they demonstate is most parsimoniously accounted for by the idea that "stages" overlap (i.e. are components in the current terminology), and they show that this makes sense of other data difficult to fit into a discrete stages framework. The approach is offered by them as an extension with the inference from under-additivity to component overlap adding precision to the investigation of RTs.

A further step from the stage viewpoint can be taken from the mathematical theorems of Townsend (1974, 1976) who has proved a high degree of equivalence between the reaction times produced under serial and parallel models. In brief, he has shown that any parallel processing model is indistinguishable from an appropriate serial model when considered on the basis of RTs. The reverse is not always true; that is, some serial models do not have equivalent parallel models, but a broad group of them do. Given this equivalence, the grounds for selecting a serial model as preferable to a parallel one cannot be firmly on the grounds of data alone, but usually reflects the experimenter's theoretical standpoint and must be justified on other grounds.

All in all, the picture is not as clear as some users of the additive factors method have presumed, as to either the definition of stages or their adequacy. Stone (1976,p.297) mentioned this confusion in the use and definition of stages, referring to "our lack of clarity regarding the definition of stages" and Sternberg's "presumption" of stages. Sternberg (1969) was aware of some of the possible pitfalls, but hoped that experimental evidence would reveal an adequate path around them. Blackman (1975) and Sanders (1977), who both use the additive factors method, have separately noted that stages are sometimes insufficient as explanations without appealing to other concepts, but still offer the best current solution to a large body of RT data. Blackman (1975) reviewed some contradictory results with the factor of relative stimulus frequency, which gives additive effects in some tasks and interacts in others, with factors such as *S-R* compatibility which are interpreted as affecting a stimulus processing stage. This led to a lack of consensus as to what stages were affected by these factors. However in his own experiment, Blackman obtained consistent interpretable results, with additivity on not only means but also second and third cumulant statistics as would be predicted under a pure serial discrete stage model. This is a clear example of the method's power within a particular study. Between studies synthesis is more difficult.

Sanders (1977) holds the additive factors/stages view, but adds to stages (which comprise the *structure* of RT) a concept of *functional* factors which may affect structure in some tasks. He successfully rationalises much of the additive factors data, mainly with the aid of the factor "practice":- for well practised subjects seem to give consistent results between studies, with contradictory finding coming mainly from less practised subjects. He developed a stage model from his review of data and new experiments, but needed to appeal to concepts beyond stages. His functional factors are seen as selectively altering the stage structure, for example he suggested that "immediate arousal is not effective when the information flow involves the response choice mechanism". That is to say, a factor which he had previously argued caused a particular pattern of results sometimes applies and sometimes does not, as governed by a functional factor.

There is some reason to conclude that processing is not purely serial (or parallel) in all RT tasks or conditions but that the style of processing varies between these two extremes. Stages are obviously essential in some tasks, as in one used by Simon, Acosta, Mewaldt and Speidel (1976). They used several conditions, but the one most directly relevant here was essentially as follows: the stimulus was a tone, either high or low, with two keys for responding, each of which could be either green or red. Subjects were instructed to press the green key on hearing a high tone, while for a low tone, the red response was correct. However, the colour of the keys varied from trial to trial and in some conditions was set zero to 350 msec after the tone was given. Obviously the subject cannot start to select his response until the colours are set. This favours a stage processing situation, especially in the 350 msec delay condition where the subject could have processed the stimulus fully into its identity as one stage and be waiting for the response selection rule to be given before proceeding with the response selection as a discrete stage. This procedure enforces stages onto the processing.

On the other hand, a partial advance information procedure used by Leonard (1958) makes overlap of stimulus identification and response selection probable. The subject faced 6 lights, arranged in an inverted V with 3 lights on each side. Responses were made by pressing one of 6 keys arranged in a 1-1 spatial correspondence with the lights, 3 in the left hand and 3 in the right. In one condition, half of the lights came on, either the left or the right 3. After a brief period, one of these went off, specifying the particular response for that trial. The initial onset of 3 lights thus gave partial stimulus information which the subject could convert into partial response selection immediately, conceivably in parallel with further stimulus processing as it became possible. That is, the subject probably processed the partial stimulus information and then prepared the corresponding hand for responding while processing the complete stimulus information given by the light's offset. This overlap of components is one form of parallel processing.

Serial-parallel differences are also possible in more common choice RT tasks. If one adopts a simple processing model (Hick 1952a) and considers a standard light-keys apparatus, as in Chapter II, one can conceive of parallel processing possibilities in a 4 choice condition that are not possible in a 2 choice version. One model explored by Hick assumes that subjects first decide in which half the stimulus occurs and then which half of that half and so on repeatedly, until the stimulus is identified precisely. So in a 4 choice condition, a subject may identify the stimulus as being in the left pair, and then as the leftmost of those. While this second identification step is proceeding, he may prepare the left hand for responding based on the result of the first step. Once again, overlap indicates parallel processing of items in different stages. This is not possible in the 2 choice - as soon as the stimulus is localised as left or right, it is completely specified, and the response can be fully selected as a second stage, which is serial since no further stimulus processing is needed.

These analyses are hypothetical, and are only included to indicate the range of serial-parallel possibilities. No attempt is made to find hard data supporting them, beyond noting their prima facie possibilities.

As can be seen from the above discussion, the issue is not clearcut, but it seems fair to conclude the stage approach should not be discarded in toto since it does allow sense to be made of much data, although it is sometimes faulty through oversimplicity, and therefore other approaches, such as the parameter one mentioned, should be developed. It has certainly widened our feeling of comprehension of RT processing and has proved to be an inspiration to a great deal of good research. The heuristic value of such a broad hypothesis seems to justify its continued use although not without qualification. In the words of Shwartz, Pomerantz and Egeth (1977), "Abandonment is too steep a price to prevent some possible misapplications." The recently suggested amendments to the additive factor method (Sanders 1977, and Stanovich and Pachella 1977) provide possible qualifications which may increase the viability of a modified stage approach to RT. However, arguments are being put forward that it is not necessary to postulate the existence of stages, at least under some circumstances. The most powerful of these appears to be the component approach of Taylor (1976), but as yet this lacks the vast array of research effort put behind the stage approach. The parameter approach which uses the additive factor method but infers additive or interacting parameters which may or may not be stages could also be useful but needs the development of a firm parametric model before more evaluation can be done. On the other hand, this approach can adopt all previous additive factor method results directly and use them to infer parameters just as the stage approach has inferred stages. The parameter approach's imprecision on the existence or otherwise of stages may prove to be an advantage, for it is possible that RT processing in some tasks has a dual nature, appearing as serial under some methods of analysis and parallel in other circumstances. This is in keeping with the theorems of Townsend (1976) and is analogous to the dual wave/corpuscular nature of light in the science of physics, where the form favoured reflects the methodology used. Certainly the chances are high that a model based on stages will be oversimplistic and inadequate to explain some tasks.

2. EXPERIMENT 3

The following experiment is to be seen against this background and attempts to do two things:- firstly to look again at the original Donders' style experiment and test his intuitive idea that the different tasks *a*, *b* and *c* involve the insertion or deletion of stages, and secondly to investigate the differences between simple and choice RT which persist even when choice RT is unaffected by the number of alternatives, N. An introduction addressed more specifically to these two points follows.

2.1 Comparing simple and choice reactions.

While it has been shown that choice reaction time (*RT*) can be independent of the number of alternative stimuli, N, in a highly compatible key-pressing task, it is still found that simple reaction is faster (Chapter I and Leonard 1959). Both of these studies used as the stimulus direct vibration of the response keys under the subjects' fingertips so that they pressed whichever of the 1, 2, 4 or 8 response keys vibrated. Simple RT was about 40 msec faster than CRT in Leonard's study, and about 25 msec in Smith's, with no difference between 2, 4 and 8 choice. In a less highly compatible situation, whatever process creates the observed increase in RT with degree of choice from 2 upwards would be extrapolated to predict a decrease from $N = 2$ to $N = 1$. As compatibility increases, the increase with N is reduced, i.e.

there is an interaction between N and compatibility, and it might be expected that the difference between $N = 1$ and $N = 2$ would decrease also. Ultimately, however, in the VT highly compatible task additional time is still needed to respond when faced with a choice of response instead of a simple reaction, even though the increase in RT with degree of choice beyond 2 has been eliminated. There must, therefore, be some difference between simple and 2 choice tasks beyond that which produces differences of RT with degree of choice in less compatible situations. If we can find the reason why this difference remains we further our understanding of the nature of simple and choice reations.

As mentioned above Donders and Külpe developed conflicting explanations of this difference. Donders (1868) postulated the subtractive principle of RT by suggesting that the overall process from stimulus to response can be split into independent additive stages. As outlined above, Donders used three related RT tasks:- *a*, the simple RT, *b*, choice RT, and *c*, the selective RT. He reported that $A = 201$ msec, $B = 284$ msec, and $C = 237$ msec from which he concluded that the response selection stage took 47 msec (B-C) and stimulus identification occupied 36 msec (C-A) in that task. In this framework, there is a qualitative difference between *a* and *b*. Külpe on the other hand argued that the difference could be quantitative, noting that greater response preparedness was possible in a simple response than if choice was called for. That is, subjects can set their motor readiness to a higher level when only one response is needed, and execute that response as soon as any stimulation arises (Woodworth 1938). It is these opposing explanations that this experiment tests.

Broadbent and Gregory (1962) argued that "the difference between *b* and *c* reactions is of the same kind as that between two- and four-choice situations, both differences being due to the need to keep varying numbers of response tendencies in readiness" and hence that $B = C$ for compatible tasks. They do not however extend the argument to cover the *a* reaction. Their results showed that *B* was not significantly different from *C* in a two stimulus VT task, i.e. doing nothing in response to a stimulus had as much effect on RT when the other stimulus was given as did selecting a different response.

There is a fourth type of task relevant to the discussion. Smith (1977) also using a VT task, measured RT in a 2-stimulus case where the same one response was made to either stimulus. One stimulus was responded to with the finger vibrated (compatible) while the other stimulus was crossed to that same finger. This will be called the *x* reaction. The *x* task is thus like *a* with neither stimulus categorization nor response selection needed. The response preparedness in *x* is arguably equal to that in *a* since the same response is made in both, regardless of the stimulus identity. Thus both Donders' and Külpe's theories would predict that the compatible component of *x* (i.e. the RT to the stimulus given to the responding finger) would equal *A*. This was indeed the case, since *X* from Smith's experiment equalled *A* from Leonard's. These RTs, together with others from Experiment 1's replication of Leonard's experiment are presented in Table 3.1. The closeness of the two-choice means in Leonard's experiment and those of Smith suggest that apparatus and subject factors were equal in all three. Thus the comparison between *A* and *X* is justified.

TABLE 3.1: Reaction times in msec to compatible vibrotactile stimuli in a range of tasks taken from various studies. See text for a description of the tasks. The value of N for b indicates the degree of choice for that condition.

	TASK			
	a	*x*	*b*	*c*
Leonard (1959)	*182*		*226(2)*	
			229(4)	
			217(8)	
Broadbent and Gregory (1962)			*193(2)*	*194*
Smith (1977)		*182*	*223(2)*	
Experiment 1 from chapter 1	*181*		*210(2)*	
			203(4)	
			216(8)	

It would seem from the results in Table 3.1 that, for VT tasks,

$$A = X < B = C \tag{3.1}$$

Since 2, 4 and 8 choice *Bs* are equal, it could be argued that stimulus categorization and reponse selection together are zero in VT tasks, since these are traditionally the stages affected by *N*, which has no effect here. So if Donders' breakdown is correct it might be expected that $A = B$, all other things being equal. As it is not, we should investigate what other things are unequal, in the light of the other relationships expressed in equation (3.1).

The difference may be due to the degree of response preparedness possible in each task, as Külpe suggested. To facilitate discussion, we define the following terms.

(a) The "comparison" response means a response made to the stimulus-response pair common to all tasks, since the RTs of such will be used as the index for comparison between tasks. In all cases in the experiment reported here it is compatible, a key press with the finger vibrated.

(b) A "latent" stimulus on any trial is a stimulus present in the task, but not given on this trial.

For example, the comparison response in *a*, *b* and *c* may be the response made to trials with vibration to the right hand index finger, when for all the tasks the correct response on these trials is right hand index finger. On such trials the latent stimulus is the left hand one for *b*, *c* and *x*. Similarly on trials on which the left hand stimulus is given, the latent stimulus is the right hand one. There is no latent stimulus in *a*.

There are two ways in which *a* and *x* differ from *b* and *c* which may mediate response preparedness. We can firstly dismiss the possibility that it is the presence of latent stimuli per se that increases the index RT, since $A = X$. However, in both *a* and *x* all responses are made with the finger of the comparison response whereas in *b* and *c* there are trials on which the comparison response is suppressed. With the same interstimulus interval (ISI) used for all tasks, this means that the temporal pattern of responses with the comparison response are more regular in *a* and *x* than in *b* and *c* where there are runs of trials not producing it. This may introduce what is effectively a foreperiod effect. That is, greater temporal certainty in response can enable greater response preparedness and hence shorter RTs (e.g. Bevan, Hardesty & Avant 1965). This may be sufficient to account for the observed pattern of RTs. Note however that the difference would seem to be something quite gross, perhaps a muscular set is either adopted or not, rather than a more complete correspondence between interresponse interval (IRI) and RT, since increasing the degree of choice increases the spread of IRIs of a comparison response slightly, but is not reflected in an increase in RT.

This variability in response frequency has been suggested as a determinant of RT by Mowbray (1960) although his concept was in terms of a ratio for each response of the number of trials with that response to trials without that response, i.e. response to nonresponse ratio, rather than straight out temporal rate (Mowbray 1962). Brebner and Gordon (1964) have shown that temporal response rate does affect RT, even with response to nonresponse ratio constant, with longer IRIs giving longer RTs. However they also showed that stimulus probability had a major effect in a *c* task with the highly compatible stimulus-response situation of digit-naming. Therefore it is unlikely that temporal variability is sufficient to cover even all highly compatible reaction time tasks, but it may be adequate for all but *c*.

A second difference between the two pairs of tasks is that *b* and *c* may be thought of as involving a response inhibition which is not present in *a* and *x* since any possible response in *b* and *c* is not made on some trials. This need for response inhibition (RI) could be reflected in a lower response preparedness resulting in longer RTs. "Response inhibition" as used here is an attribute of a response, which is not to be made on presentation of some stimuli, rather than of the task as a whole, as in *c* where all responses to stimulus 2 must be suppressed. There may be a response inhibition subprocess which accounts for the additional time taken by the comparison response in *b* and *c* or perhaps it acts indirectly, e.g. via response preparedness. The RI hypothesis is well described by Kornblum (1965) as "the hypothesis that a measurable portion of the reaction time interval is consumed by processes associated with the inhibition of incorrect alternative responses", and he presents evidence consistent with it.

This idea appears more elegant than the variability of IRI as it can predict precisely the pattern of results in Table 3.1. No inhibition of the response is needed on any trial in *a* or *x* and these have equal RTs. The other two, *b* and *c* involve two stimuli and both have equal RI and their equal RTs are greater than *A* and *X*. In general, the higher the degree of choice in *b* tasks, the more responses there are to be inhibited, and this greater inhibition is reflected in increasing RTs. However, for highly compatible situations the inhibition factor must be assumed to be equal for all degrees of choice greater than 2, so that the choice times will be independent of *N* as found in Chapter I. That is, in such tasks RI is of an all or none nature.

It is possible to differentiate between RI and temporal uncertainty as explanations by using a condition in which the contrast response is matched in time of occurrence to that of *b* and *c*, but no response inhibition is needed. A modification of *c* will achieve this. Instead of giving trials with the noncomparison stimulus to which no response is made, blank trials (i.e. "trials" with no stimulus and no response) are given. This will be called a *t* task. That is, the comparison response occurs at the same intervals for *b*, *c* and *t*, while the remainder of the trials have either another stimulus calling for a different response (*b*), or another stimulus calling for no response (*c*), or no stimulus and no response only elapsed time, (*t*).

Consider what the various theories would predict for this task. In the Donders' framework, *t* is a simple reaction task with unusual ISIs, but still lacks stages (2) and (3), and so *T* should almost equal *A* and certainly be less than *B*. Response preparedness through response inhibition would also predict $T = A$, since in neither are there any trials on which the comparison response has to be inhibited. On the other hand, the temporal uncertainty version gives $T = B$, for in both the comparison response occurs with equal IRIs by design. These five tasks then should indicate which explanation is most justified.

2.2 *Method*

Apparatus

The vibro-tactile apparatus used in this experiment was described in Chapter I. The experiment was controlled by a LINK-8 computer housed in an adjacent room which recorded the response made and the RT. Only the innermost 2 keys corresponding to the left and right index fingers were used in this experiment.

Subjects

Ten women from the subject panel of the Oxford University Institute of Experimental Psychology were paid to participate. Their ages ranged from 18 to 27 years.

TABLE 3.2: A description of the 5 tasks used in terms of their two equiprobable states, and the corresponding stimulus-response pairs. The symbol Ø represents the null condition, i.e. no response or no stimulus.

Note that all tasks contain the index response, 1 - 1.

See text for further explanation.

Task	*State 1* stimulus - response	*State 2* stimulus - response
a	1 - 1	1 - 1
x	1 - 1	2 - 1
t	1 - 1	Ø
b	1 - 1	2 - 2
c	1 - 1	2 - Ø

Procedure

The five tasks described above were used, namely *a*, *x*, *t*, *b* and *c*. Table 3.2 gives each in terms of 2 equiprobable states; i.e. which stimulus each state produced in the various tasks and which response was correct for that stimulus. One of these two possible states occurred on each trial, with a response-stimulus interval of 2.0 to 2.5 sec. For example consider *c*. Table 3.2 shows that state 1 produced stimulus 1, calling for a compatible response while state 2 gave the other stimulus which was to be ignored. This second stimulus stayed on for .5 second in lieu of a response. Subjects kept both fingers on the keys in all five tasks, even if only one was used in responding.

For each task there were 154 trials, preceded by 12 warm-up trials excluded from the analysis. The stimulus-response pair listed as 1 → 1 in Table 3.2 was the contrast response common to all tasks. For half the subjects this corresponded to the left index finger, and for the others it was the right index finger. Each subject did each task once on each of two days, with the other of tasks balanced between subjects in a Latin square design.

At the start of the experiment the function of the apparatus was described to each subject, and this was followed by 12 trials to familiarize her with the feel of the stimuli and the responses needed. The sequence of the two stimuli in the familiarization trials was two left then two right, repeated 3 times. The subject was told this so that it was not practice for the *b* task to follow, since it lacked any stimulus uncertainty and subjects were instructed not to hurry. Each task was then described and given to the subject in the appropriate order.

2.3 Results

The mean correct response times for the comparison response in each task are plotted in Figure 3.1 for day 1 and day 2. Data for individual subjects are given in Appendix 3. Results from day 1 and day 2 are substantially the same, and only those from the more practised day 2 will be discussed in

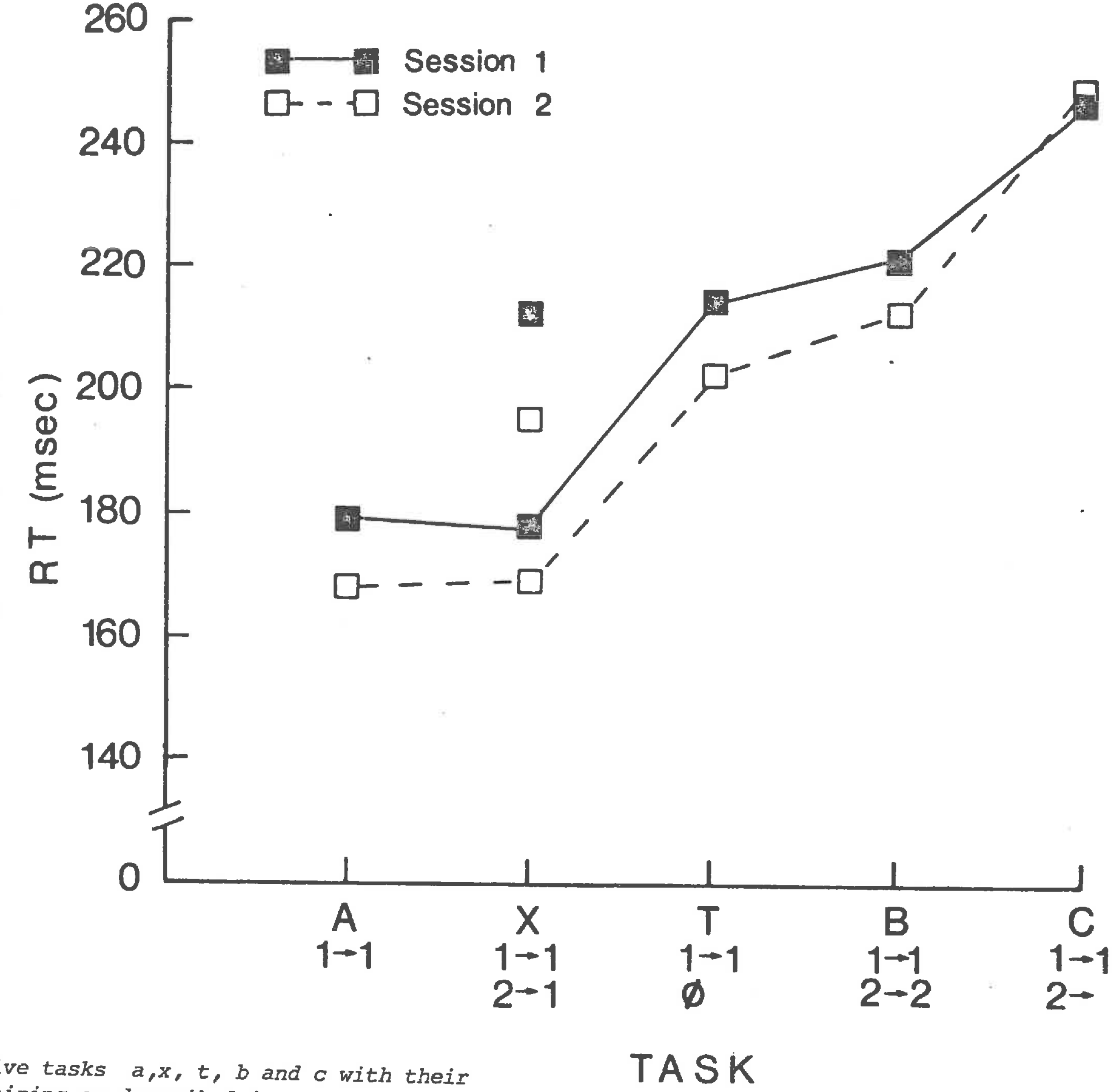

FIGURE 3.1: RT (msec) for the five tasks a,x, t, b and c with their stimulus response pairing as described in the text. The two isolated points for x are the RTs for the incompatible S-R pair present in that task.

detail as they are less variable. Consideration of either day would lead to similar conclusions. An analysis of variance showed that the task effect was significant ($F_{4,20}$ = 48.5, p < .0001). The full analysis table is given in Appendix 3. Post hoc analysis (Duncan's multiple range test) produced three subsets with significant differences between the sets but not within at α = 0.05. Group 1 was *A* and *X*, group 2 was *T* and *B* and group 3 was *C*.

There was no significant difference between the subjects whose comparison response was with the right hand and those with the left on any task (t_8 = .19, .04, -.73, and -.85 for *a*, *x*, *t*, *b* and *c* respectively, with the critical t = 2.30 at α = .05).

Contrasting the comparison and other response times for *b* also showed no significant difference (t_9 = .62, critical t = 2.26 at α = 0.05). Thus the 2 stimuli and responses used can be accepted as equivalent.

In *x* there was a significant difference between the comparison response (compatible) and the other (stimulus 2 but response 1), with the other significantly longer (t_9 = 4.5, critical t = 1.83, one tailed). This suggests that the subjects were not responding in this task to a possible auditory or other cue, since this would give equal RTs, but to the vibration.

2.4 *Discussion*

The result *B* < *C* is unusual but not altogether unexpected, although using equivalent apparatus, Broadbent and Gregory (1962) reported no significant difference between *B* and *C*. However, they do not specify for how long the stimulus to be ignored in *c* was left on. Their study may have used a different duration of the ignored stimulus, perhaps shorter than the 0.5 sec (about 2 reaction times) used in this study, and if a longer stimulus can be considered as being more intense, then the result found by John (1966) would explain the discrepancy. In that experiment, subjects had to press a button in response to the onset of the light. Under *a* conditions, the subjects responded to the sound as to the light, and in the *c* condition, they ignored it. Two intensities of sound, loud and soft, were used in separate blocks of trials. In the *a* conditions, the RT to the light was unaffected by the intensity of the sound, but in *c*, RT to the light was significantly longer if the stimulus to be ignored was loud. That is, the greater the intensity (corresponding to duration in this case) of the stimulus to be ignored, the longer the comparison RT.

Other evidence comes from studies which have used naming digits presented visually, also a highly compatible task. Forrin and Morin (1966) found $B < C$ in such a task. Their *c* task used the digits 1-8 with subjects responding with "2" and "8" or with "2", "4", "7" and "8" to the corresponding stimuli and ignoring the rest. The *b* task controls used the stimuli corresponding to the two or four member response sets of the *c* condition, or all 8, and found that the 2, 4 and 8 choice *B*s were each less than the 2- or 4-response *C*s. Mowbray (1960) had subjects respond to 1 or all of 2, 4, 6, 8 or 10 numerals, and found that $B > C$ for 2, 4 and 6 stimuli, but $B < C$ with 8 or 10.

The study by John (1966) linking intensity of the ignored stimulus and the comparison RT is again relevant since if a highly compatible stimulus is considered as evoking its response intensely, $B < C$ could then be expected in line with his results.

The results of the experiment reported here allow an assessment of the rival theories detailed earlier. This is summarised in Table 3.3 and is explained in the following paragraphs. To distinguish between the RTs from the two stimuli in X, let X_1 be the RT from stimulus 1, and X_2 for stimulus 2.

TABLE 3.3: The ability of 3 theories described in the text to explain aspects of the results from experiment 3. Each entry is under an "equals" or a "less than" sign, indicating whether or not that theory can explain the observed relationship between the paired RTs. "Extended" means that an extended version theory can explain the result although the simple version cannot. All three predict that $A < C$ and $A < B$. The right-most comparison is between the RTs for the two stimuli used in task X.

See the text for a fuller description.

Theory	Observed relationship between RT				
	$A = X_1$	$X_1 < T$	$T = B$	$B < C$	$X_1 < X_2$
Donders	*Yes*	*No*	*No*	*No*	*No*
Response Inhibition	*Yes*	*No*	*No*	*Extended*	*Extended*
Temporal Uncertainty	*Yes*	*Yes*	*Yes*	*Extended*	*Extended*

1) Donders' subtractive stage approach

The data presented here must be interpreted as being against the simple application of Donders' subtractive stage principle in which changes in the task change the stages needed, with larger RTs reflecting more stages. Coupled with the difficulty it has in explaining no rise in RT with N in b tasks although $A < B$, it is apparent firstly $B < C$ is impossible (adding a response selection stage cannot reduce RT); nor can T exceed A, since both are forms of the simple reaction; nor could $T=B$ since t lacks the proposed stimulus identification stage of b. The difference between the RTs from the two stimuli in x is also difficult to account for, since Donders did not consider the description of stages for nonhomogeneous tasks with more than one S-R association. A longer response selection stage for the incompatible response is the most adequate explanation. This complicates the model, introducing the need to determine whether a longer RT reflects more stages or the same, but longer, stages. The data do not favour the simple form of Donders' model as it can explain few of the observed relationships between the RTs.

2) Külpe's qualitative differences

Külpe's general idea of response preparedness on the other hand gives a good fit to most of the data. Response preparedness should be higher for a and x than for t, b and c, and therefore A and X should be shorter than the rest as found. We can also choose between the two possible mediators of response preparedness discussed above, namely response inhibition and temporal uncertainty.

(i) Response inhibition (RI).

As an explanation of RT, the need to inhibit the comparison response on some trials is not well supported by the data. The equality of A and X_1 is explicable, since the comparison response is not inhibited on any trials in either *a* or *x*. The relationship between *A* and *T*, and *T* and *B* are not. Response inhibition is not present in *t*, yet $T > A$, and while in the *b* the comparison response is inhibited on some trials, yet it was found that $T=B$. This approach can, however, explain the comparison of *A* or *X*, (no RI) with *B* (with RI).

The simple RI theory does not account for $X_1 < X_2$. Perhaps inhibiting a compatible response to the given stimulus, as is required for X_2, takes longer than no inhibition, as required for X_1, and therefore $X_1 < X_2$. Another extension is needed to explain why $B < C$. This can be done by assuming that the need to suppress the compatible response <u>and all others</u> to the latent stimulus, i.e. inhibit it completely, flows over to the comparison response, increasing its inhibition in sympathy and raising its RT, giving $B < C$. This principle would not apply in *x*, since a response is allowed to stimulus 2, and this perhaps avoids a sympathetic effect on X_1. However, in the more common case in which $B < C$, this explanation breaks down. Other extensions are possible, but prove no more adequate.

These additions make the RI concept quite complex, and yet it is still not satisfactory - e.g. it cannot explain why $A < T$ or $T=B$. In fact it can be discarded in favour of temporal uncertainty.

This is not to say that response inhibition is without effect. Obviously it can affect RT since including catch trials in a simple reaction task lengthens RT. Nor does it preclude RI from interacting with other recognised parameters of RT in choice tasks, but it is not a sufficient explanation even in this situation where any confounding with compatibility is arguably negligible and so allows a more pure estimate of its effect.

(ii) Temporal uncertainty (TU).

The data do suggest that temporal uncertainty is a major determinant of RT at this level of compatibility since $T = B$. That is, a simple and a choice task with equal occurrences in time of the index response have equal RTs. Additional confirmation comes from x, since we find that $X = A$ as predicted by temporary uncertainty.

Also, X and A are less than T and B, i.e. responses with more variable time of occurrence are slower than regular ones, as this theory predicts.

Applying this principle simplistically, however, gives no difference between X_1 and X_2. To account for the difference we can perhaps reasonably appeal to the concept of compatibility, with a less compatible response taking longer than a compatible one. It is apparent that the response is less compatible for X_2 than for X_1, and its RT is longer.

This still leaves $B < C$, while the TU principle would have $B = C$, since their responses are matched in time. It is clear from this result that the latent stimulus is affecting the comparison RT, and it shows that the task must be considered as a whole, not just via the comparison response. In addition the latent stimulus presence in the task affects the comparison RT, increasing (or decreasing) it if the latent stimulus is less (or more) compatible and the extent of this change is determined by the latent stimulus-response pair's compatibility. This will be called the latent stimulus effect and will be dealt with in greater detail in Chapter IV.

It seems likely that to suppress a compatible response to a VT stimulus is less compatible than to respond, while the reverse holds for less compatible tasks in which RT does increase with N. The latent stimulus being less compatible in c than in b, it follows that $B < C$. For other stimulus-response types such as the lights and keys as in Chapter II, responding is less compatible than not responding, and so $B > C$.

Data consistent with this idea come from the experiment by Mowbray (1960) using the highly compatible digit naming task, since the presence of a lower compatibility response (ignoring the presented digit) would result in RT's increasing with N in such c tasks. This is what Mowbray found. However, while response preparedness is an adequate predictor for his data, the operating variable is not the ratio of response to nonresponse trials as he suggests, since this would predict that $A = T$.

This suggestion of differences in compatibility between responding and nonresponding follows an equivalent argument by Brebner and Gordon (1964) who note that while one of the tasks Mowbray and they use is overlearnt (naming numerals) the other, naming selectively is not. They further suggest that "the differences in latencies observed in selective response tasks may disappear with prolonged practice". In the data presented here, C is affected only slightly by practice, and less than any of the other tasks. What would happen with larger amounts of practice is not apparent.

Unfortunately, the latent stimulus principle upsets the equality of A and X_1. Since X_2 is less compatible than

X_1, it should affect X_1, increasing it beyond that predicted by *TU*, i.e. *A*. This was not found. So while temporal uncertainty is the best explanation of the three tested here, it is still not fully successful.

2.5 Conclusions

The success of the *TU* model in predicting $A = X_1 < T = B$, i.e. the order of the comparison RTs from all but *C*, suggests that a major part of the reason why simple RT is shorter than choice RT lies in the greater response preparedness possible in a simple reaction, which is directly testable in a VT situation where the independence of RT and *N* enables it to be assessed free from differences unavoidable with less compatible tasks.

However, on its own it fails to account for $X_1 < X_2$ and $B < C$. These results show that it is not sufficient merely to consider a particular stimulus' compatibility with its response as this is the same for the index response in all five tasks. Instead it is essential to examine the whole task (Kornblum 1965). In particular these data should be considered as to the effect of the latent stimulus on the contrast response and how this interaction is affected by the compatibility of the latent stimulus. The results can be interpreted, in a manner orthogonal to the response preparedness approach, as showing that the less compatible the latent stimulus with its response, the more it lengthens RT. That is, a latent stimulus-response that is so compatible as to give no increase with *N* has the same effect as empty time ($B = T$), while the stimulus-response association of VT stimulus to no response which is less compatible (as argued above) increases the comparison RT ($B < C$). It was suggested above that response preparedness can be greater for a response when the time it is to be made is more regular, which gives $A < T$. With these two principles, the effect of latent stimuli and of response preparedness, we can thus explain $A < T = B < C$. The task x involves the interaction of these two principles, with the latent stimulus less compatible (Smith 1977) but a regular response with the contrast key. The result obtained here, $A = X_1$ is the result predicted solely on the basis of response preparedness, with no increase through the less compatible latent stimulus. The accelerating model described in the following chapter incorporates these two principles and completely fits the data found here, including why X_1 is less than expected.

CHAPTER IV

MODELS OF CHOICE REACTION TIME

1.1 Preamble

Before reviewing relevant models of choice reaction processing, it is useful to consider the general problem of modelling. By modelling is meant a set of specifications more or less closely tied to some theory, which describes the measured variable, RT in this case, under specified conditions. Any accompanying theory must be explanatory and a valid representation or analogue of the behaviour being modelled. A complete model will match experimental data in every testable respect, but this is seldom attempted. Ultimately it may be possible to develop a model which emulates the full complexities of choice reaction behaviour, but certainly no current model does this. The path to a complete model must be via successive approximations, for which one must decide which aspects are of primary interest, and concentrate on them. In this way we try to add to our understanding by simplifying the model to an acceptable level. As Edwards (1965) pessimistically noted concerning a model which he developed, "No model that makes many specific and easily checkable predictions has any possibility of being consistent with substantial amounts of data: only vague models or models with plenty of fittable parameters survive such confrontations."

So models must be developed for a set purpose and a limited domain of interest selected after assessing the costs and payoffs of comprehensive accuracy versus comprehensible but restricted application. This means that direct comparisons of models must be approached with caution as each tackles a slightly different area of RT knowledge. The usual method involves classifying models on a few broad dimensions and is arguably the fairest. For example, Audley and Pike (1965) separated 3 groups of models which they classified as statistical uncertainty models, markov chain models, and stimulus sampling to criterion models, choosing the latter as the best approach for modelling RT, while Welford (1976) used the dichotomy, serial versus simultaneous processing.

All choice RT models follow broadly similar lines:- the subject starts a trial without knowledge of the particular stimulus (although possibly with expectations) and either repeatedly takes evidence about the stimulus or its preprocessed internal representation, or analyses deeper the evidence gained to date, until one possibility is adequately supported, on the basis of the current sample or accumulated evidence from discrete or continuous samples. Models can be differentiated along 2 separate aspects: how the fate of each alternative changes during a trial and the time course of these changes. Each model favours a different "criterion dimension", by which is meant broadly the transformation of the stimulus input on which the alternatives are assessed. For example, in one model this involves a complete matching of the received stimulus with internal representations of the alternatives, while another assesses the probability that the received input comes from each possibility. Models also vary as to the "criterion state" used, i.e. the grounds for deciding that one alternative is the best choice on the current trial. This will be explained in context for each model. This is not to say that such representation would be viewed by each model's originator as in the spirit of his model, but is superimposed by this reviewer to facilitate direct comparisons of the models.

Two broad classes of models can be distinguished on the basis of the style of criterion state they employ. Some models completely reject alternatives during the trial before the final choice is made, and other keep assessing each possibility relative to others until one is sufficiently justified to be accepted. These can be called *complete criterion* models and *relative criterion* models. In the first of these, the processing of the alternatives is complete in that they are all assessed to the level of rejection apart from the one which is chosen. The decision in these models is simple, merely choosing the only non-rejected option. In relative criterion models on the other hand, none of the alternatives is discarded prior to the decision point. In general, these models assess the evidence in favour of each alternative until one is deemed adequate in its own right or superior to the rest. The two types will become clearer with the presentation of actual examples as below.

The major areas of interest here are the relationship between mean RT and the probabilities of the alternatives, given

$$\mathrm{RT} = A + B . \sum_{i=1}^{N} (-p_i log\ p_i) \qquad 4.0$$

which reduced to a log increase in RT with N for equiprobable stimuli:

$$RT = A + B.log(N + D) \qquad 0 \leqslant D \leqslant 1 \qquad 4.1$$

as explained in Chapter I, and the range of values of B (and its reciprocal, C, the compatibility), obtained from various tasks. Models which do not cover these points will not be detailed here, although the recent model of Grice, Nullmeyer and Spiker (1977) deserves a mention as a good attempt to describe the distribution of RT rather than just its mean - without, however, considering its increase with N. Other models are put forward only in terms of $N = 2$, without specifying how they apply for larger N. These also will not be considered.

2. COMPLETE CRITERION MODELS

2.1 Successive group elimination models

Hick (1952a) designed one of the simplest models of the choice process. He suggested that the subject makes a chain of subdecisions or steps each of equal duration, which Welford (1971) called an "inspection time". One subdecision locates the stimulus as being in half of the remaining possibilities, and rejects the others. This process is repeated until only one alternative is left whereupon the corresponding response is selected and made. Under this successive dichotomization, the number of steps equals log_2N, at least where N is a power of 2. For example if the subject has 8 alternatives, at the start of the trial any one of the eight may be correct. During the first inspection time, 4 of these are rejected and the other

4 are left. Two of these are discarded in the second inspection time. The third and final step chooses between the remaining two, rejecting one and leaving the selected alternative. The criterion dimension is matching between the stimulus and internal representations, or templates, of the possible stimuli, and each possibility is processed i.e. to rejection or acceptance completely.

Since Hick found that $log(N + 1)$ gave a better fit than $log(N)$, he suggested that the effective number of alternatives was one more than the number of stimuli. He felt that this additional one represented the fact that subjects had to decide not only which of N stimuli had occurred but whether any stimulus had occurred, and hence had to decide between the N stimulus states and one nonstimulus state. If N is not a power of 2, the processor is faced with an odd number of possibilities in at least one stage. When this happens an unequal division is made, and one of the subgroups is rejected. The model suggests that there should be evidence of a periodicity in the RTs corresponding to the inspection time. Such lumpiness was not apparent in the RT distributions Hick examined. More recently, Stone (1976) reviewed the evidence for periodicity in RT distributions, and concluded that it has not been found. Nor can the model predict observed differences in RTs to stimuli of unequal probabilities, with the more probable stimuli being reacted to faster. To overcome this, Welford (1960) extended the model so that cognitive strategies can be adopted which influence RT. Like Hick, he envisaged a series of steps, each searching for the stimulus in half the remaining alternatives, but he proposed that the subject must test a matching half set before proceeding to the next step. Thus for $N = 4$, the subject compares the given stimulus with 2 of the alternatives. If the stimulus is in that half set, he proceeds immediately with the next dichotomization; if not, he checks the other two, and gets a match there before moving to the next step. Each halving subdecision takes either 1 or 2 inspection times. If the stimuli are equi-probable and random, each step will take 1.5 inspections on average. However, if one stimulus or group of stimuli are more frequent, the subject can check the half containing them first and the other group second. This means that the more probable stimuli are located faster than the less probable ones, which tallies with the result found. Welford (1973) has produced a measure of "inspection time", and has used it subsequently (Welford 1975) to provide evidence in favour of the model by finding search strategies which give the measured RTs for assorted stimulus arrays. However, neither model can describe tasks in which RT is unaffacted by N as discussed in Chapter I.

2.2 *Successive individual elimination*

Luce (1960, 1963) produced a model of choice RT based on the choice axiom. This axiom can be summarized as follows: If pair-wise discrimination between a set of alternative responses is imperfect, then the probabilities of choice from a subset, R, are in the same ratio to each other as they are in the entire response set, and if one response is never preferred to another, then it will never be made and may be excluded. Additional to this axiom, Luce postulated that a subject successively rejects possible responses one at a time until only one is left. The RT is the sum of the constituent rejection times. This can be developed mathematically to show that if the individual rejection times follow a Gamma distribution, then

$$\mathrm{RT} = A + B\sum_j(-q_j\ Log\ q_j) \qquad 4.2$$

where q_j is the probability of the subject making response j. With negligible error rates, and stimulus i associated with response j, q_j will equal p_i and this equation reduces to the more usual form as in equation 4.0. With all q_js equal it reduces to 4.1 as required.

This model has been criticised for its concentation on response effects to the exclusion of stimulus effects such as the more similar the stimulus set, the longer the RT, even with the same responses. Laming (1968) found experimentally that RT was not a linear function of $q_j.log(q_j)$ and has more recently argued cogently that "the choice axiom fails when there is a natural organisation of the stimuli sufficiently salient to influence the choices made" (Laming 1977a,b). Nor does the model account for the range of Bs obtainable with the same responses and stimuli, but with different S-R associations (e.g. Brainard, Irby, Fitts & Alluisi, 1962). It is, however, a useful attempt to tie choice RT in with other choice behaviour.

2.3 Contemporaneous complete identification

An alternative to the successive elimination of groups or individual possibilities, but still using a complete criterion occurs in a model by Rapoport (1959). It stems from one of the suggestions made earlier by Christie and Luce (1956). They suggested that choice between N alternative could be described generally as involving N elementary decisions, taking place either serially or in parallel and they pointed out that either type of process could be specified by a directed graph, or Markov chain. Luce (1960) developed the strict serial alternative as detailed above while Rapoport (1959) favoured a strict parallel approach.

Rapoport assumed that choice RT consisted of processing all N possibilities completely (i.e. to a "yes" or a "no") and exhaustively (i.e. the response was made only after all N elementary processes had finished. Each elementary process is independent of the others, in that its duration is unaffected by the number of others present or whether they have finished, even if a completed one resulted in a "yes". The RT is thus the maximum of the N independent elementary process durations. If each such duration is drawn from an exponential distribution, which Rapoport suggested is well-founded neurologically, the mean RT varies with the logarithm of N .

Rapoport was one of the first to mention explicitly that the processing time in his model involves both stimulus recognition and response selection, and is influenced by factors which affect either component.

Laming (1966) described a very similar model in slightly different mathematical style. He developed his argument via the discrete approximation to the logarithmic function,

$$log(M) \simeq \sum_{i=1}^{M} \frac{1}{r}$$

where M is a positive integer, which suggests that (4.1) can be rewritten as

$$\mathrm{RT} = A + B \sum_{r=1}^{N} \frac{1}{r} \qquad 4.3$$

Using Hick's formulation that RT is proportional to $log(N+1)$ rather than the hybrid Hick/Hyman form of (4.1), this can be converted to

$$RT = A + B \sum_{r=1}^{N} \frac{1}{r} \qquad 4.4$$

Laming then generalized these two equations into

$$RT = A + B \sum_{r=1}^{N} \frac{1}{r+k} \qquad 4.5$$

Obviously equation 4.5 will give as good a fit to experimental data as the better of (4.3) and (4.4) for some value of k between 0 and 1, but Laming treated the more general case of $k \geqslant -1$. He developed the mathematical formula for a family of elementary process time distributions for which the maximum (i.e. the last of N parallel processes to finish) satisfies (4.5). If $k = 0$, the distribution is exponential as in Rapoport's version. Mathematical treatment for other values of k has been explored by Laming (1966) who also fitted RT variances predicted by the model to experimental data. Since the treatment is complex and the general principles are covered in the outline above, it will not be reproduced here. One point of interest in this model is the generalization parameter, k. Laming noted that it would probably be possible to produce a better fit to experimental data than either Hick's or Hyman's formulae given by selecting a suitable value for k in (4.5). This point will be returned to later in the description of the new model proposed here.

3. RELATIVE CRITERION MODELS

These models embody the idea of processing on each trial as the sampling over time of evidence for the stimuli, forming tentative identities from each sample and assessing the accumulated evidence until one alternative gains sufficient support relative to the others. The terms "evidence" and "tentative identification" (*TI*) refer to different aspects of the decision process. Evidence is a loose concept referring to the value of the current imperfect internal representation of the stimulus and is a continuous variable, being either a direct neural representation of the stimulus or some simple transform of it. In contrast, a *TI* is formed in some models and is the best guess for the stimulus' identity based on the current sample of evidence. Effectively a *TI* labels the sample as being from one of the alternatives and thus takes only discrete values. Since the evidence is imperfect, a *TI* may not be correct. The criterion for decision is not absolute identity or binary information (yes/no) as it is for complete criterion models, but a value on a particular scale. All involve the collected evidence for each stimulus changing with time until the model's criterion is reached. Mathematically these can be represented or approximated by markov chains, i.e. sequences of possible states which can be specified by the amount of evidence for all alternatives in the set, with absorption states, i.e. those at which a final decision is made, being defined by the response criterion. The major difference between the various models of this type is in the particular response criterion adopted.

3.1 Criterion: repetition of TI

In these models, the first alternative which the processor produces as the *TI* in *K* successive samples is taken as correct. Audley (1960) and Kintsch (1963) have put forward models based on this criterion. Audley developed a general form for a range of *K* and produced the generating functions for $K > 2$ (Audley & Pike 1965), while Kintsch restricted himself to treating $K = 2$, with the duration of each step or *TI* being distributed exponentially. Audley showed that this model predicts that error responses will be longer on average than correct responses, which is usually not so in choice reaction data.

The processing in the model may be described as follows. All alternatives have an initial count or score of zero. Successive *TI*s of the alternative given are produced, and the corresponding score is incremented by 1. If it was zero, then the former *TI*'s score is set to zero. Processing continues until a score accumulates to *K*, when the response is made. This only happens when *K* successive *TI*s are identical. The processor acts like a faulty memory, forgetting all previous evidence when the *TI* changes between samples.

3.2 Criterion: One alternative more likely than chance

One early model of this form was sketched briefly by Hick (1962b). In that model, all possibilities are imagined as comprising a range of sensory input divided into *N* states of equal probability, representing the a priori probability of any one state. If the probability of a state vanishing is fixed at τ/K for any instant at τ, the probability of a state lasting as long as τ msec is $e^{-\tau/K}$. When the input has stayed in one state for τ msec such that its probability of lasting that long, $e^{-\tau/K}$, becomes just less than the a priori probability, $^{1}/_{N}$, since the input was in that state for longer than would be expected from the a priori probability that state is chosen to initiate the response. The decision in this model is analogous to a statistical decision to reject a null hypothesis. Hick did not expand this outline, but others have since used the idea of a continuing statistical test as the decision mechanism.

3.3 Criterion: Most evidence from a preset sample size

Stone (1960) presented a model which draws an analogy between choice RT processing and a fixed sample size statistical decision. He assumed that the decision mechanism keeps a running total of successive samples of some transform of the data from each possible stimulus. If the criterion is set for Q samples, then the duration of the decision process is Q times the time between samples, which is assumed to be constant for simplicity. The decision procedure is based on N running totals or accumulators such that the stimulus corresponding to the largest total at the criterion time is chosen.

Stone assumed that this decision is made after Q samples, where Q is set prior to the trial to the value which maximizes the subject's overall chance of success, as measured by the sequential probability ratio. Unfortunately this model has a major theoretical flaw. As the sample size is set prior to the start of the trial, the particular stimulus given can have no effect on the RT of that trial, which is not the case. As mentioned previously, for example, the probability of the given stimulus significantly influences its RT.

Edwards (1965) replaced this fixed sample size feature with an assumption that the subject decides after each sample whether or not to take another. He adopted a Bayesian approach, taking explicit account of the costs and payoffs in the decision to stop or continue sampling. If the cost in terms of time (or other experimental penalties) is greater than the payoff for additional accuracy, the subject will stop, and make the currently most favoured response. This approach is attractive, but the difficulties in assessing what are the costs and payoffs inherent in a typical RT task detract considerably from its usefulness.

3.4 Criterion: A preset number of TIs

Another model is that of La Berge (1962). Rather than accumulating evidence from each sample, a *TI* is produced based on that sample, and this is tallied against the corresponding response. The criterion decision is that the first tally to reach a criterion total initiates its response and the sampling stops. This decision process is equivalent to a series of independent multinomial trials which continue until one outcome has occurred a preset number of times. From this model La Berge developed the relationship between RT and response probabilities for $N = 2$ into incomplete beta ratios. Laming (1968,p.24) produced a further prediction from this model, namely that error latencies are longer than correct latencies, on which he found contrary evidence. However, reanalysis arising from a plausible simple suggestion can circumvent this apparent flaw and will be discussed in section 6 (p.99).

3.5 Criterion: sufficiently more evidence for one alternative

The random walk model extensively developed by Laming (1968) from the sequential probability ratio test approach of Stone (1960) is best understood in the case for $N = 2$. The principles are the same for $N > 2$ and have been detailed by Laming (1968) but will only be given briefly here. On each trial, the subject takes a stream of evidence from the stimulus. This evidence is not veridical, and takes a continuous range of values distributed about the true identity along a hypothetical underlying dimension. The evidence in favour of each alternative is added to its current total and the first to get adequately more evidence than its opponents determines the response made.

For $N = 2$, two scores are initially zero. Each sample of the stimulus gathered in successive small time slices are converted to corresponding amounts of evidence in favour of S_1 and S_2, the two possible stimuli. These amounts are added to their corresponding scores. When a score exceeds the other by a predetermined amount, that response is initiated. The increment from each sample for S_1 is the logarithm of the probability that such a sample could occur given that S_1 is presented. Actually, Laming presented his model in terms of one score for $N = 2$, with each sample adding or subtracting an amount equal to the difference between the amounts added to S_1's and S_2's scores in this description. These approaches are conceptually equivalent, and the one presented here extends more readily to $N > 2$, as follows.

In general, N scores are kept, each incrementing from the samples by an amount specified as for $N = 2$, i.e. the logarithm of the probability that the sample came from a trial on which its stimulus was presented. A more rigorous description in more complex probability terms is given in Laming (1968).

Laming explored this model and found that it could explain a range of experimental results including the relationship between RT and p_is expressed in equation (4.0). This has been developed into quite a comprehensive model, although it skirts the issue of S-R compatibility which is of prime concern in this research.

4. FAST AND SLOW DISTRIBUTION MODELS

Falmagne (1965) and Kornblum (1969) have proposed theories of RT in which the RT on any trial is drawn from one of two distributions of times, one fast and one slow. The more general model is that of Falmagne. The subject is seen as learning to expect certain stimuli on each trial. Based on his expectancy he differentially prepares for the stimuli. If the stimulus presented is one for which he prepared, the RT is drawn from the distribution of fast times, and if not, from the slow distribution. The expectancy is set in part by the subjective assessed probabilities of the stimuli based on their recent relative frequencies.

Falmagne showed that this can account for speed-accuracy tradeoffs (RT decreases as error rate increases), the relationship between RT and $\log N$, (equation 4.1), unequal stimulus frequencies ($RT_i < RT_j$ if $p_i > p_j$) and repetition effects (repeated stimuli are responded to faster than alternations). In fact the model is derived in part from a study by Bértelson (1963) in which he demonstrated the repetition effect and found that S-R compatibility had more effect on alternations than on repetitions. This is a quite impressive list of successful matchings between theory and data, but leaves unexplained the source of the processing time difference beyond appealing to the idea of preparation. That is, the actual mechanics of identification as the expected stimulus or a particular other is not specified.

Kornblum (1969) used a similar framework for his model, replacing the concept of preparation with the specific effect of repetitions and gave a fuller description of the origin of the RT difference. The subject checks whether the stimulus on this trial is the same as that given on the previous one, and if so the RT is shorter than if the stimulus changes. This he attributed to the subject's not needing to process the stimulus fully if it was a repetition, because all the relevant checks and response selection mechanisms are still set for that stimulus. If the stimulus changes, however, this shortcut check fails, and the stimulus must be fully processed. Since the proportion of repetitions is confounded with the information metric, $H = \Sigma(-p_i . \log p_i)$, as N varies, this model gives an alternative explanation of equation (4.0). Kornblum showed that his analysis gave better fits to the data from experiments designed to unconfound repetition percentage and H than did models based on H. One difficulty with this model is that repetition effects are usually found for short response-stimulus intervals (*RSI*s), say less than 0.5 sec, although Kornblum (1973) listed some studies in which a repetition effect is still present at *RSI*s of 10 seconds and more. With longer *RSI*s repetitions are sometimes slower than changes (Kirby 1974), yet the relationship of equation (4.1) still holds. Hawkins and his co-workers (Hawkins & Hosking 1969; Hawkins, Thomas & Drury 1970) failed to find any sequential effects in their data. These points preclude the differences in RT always being attributed to differential repetition/nonrepetition RTs.

5. THE NEED FOR A NEW MODEL

5.1 Given the vast array of RT experiments, it is always possible to select an area which a particular model cannot describe adequately. If the area of discrepancy is important enough, a new model is needed. One such area is very high compatibility. Apart from the last two models mentioned, those reviewed above imply that some increase in RT with N must occur. This has been shown not to be the case for some choice RT tasks in Chapters I and II.

Models of the Complete Criterion type would need decision processes taking no time (or at least having zero variance for the models in section 2.3) when RT is independent of N. For example each step in Welford's successive dichotomization model must take zero time or else RT will increase with the number of steps which is proportional to $\log_2 N$. A step taking no time is difficult to envisage. Similarly an exponential distribution with zero variance has zero mean, so Rapoport's contemporaneous complete identification model becomes improbable when RT is independent of N. Indeed for a range of possible B values, a corresponding range of exponential distribution variances is required, and as B tends to zero, so must the variance and mean of the exponential distribution of elementary decision times. This is plausible except in the limit at zero. Luce's (1960) model, with N successive steps, fails under the same argument.

Similar arguments hold for models with relative criteria:- no increase in processing time with N implies an infinitely fast sampling of evidence or formation of TIs, which is implausible and against the spirit of this type of model.

The models of Falmagne and Kornblum can account for this result in a post hoc fashion. For the former it is sufficient to say that preparation is maximal for all possibilities, and so the two assumed distributions are actually only one. Similarly if RTs to repetitions equal RTs for changed stimuli, Kornblum's model will predict no increase in RT with N. However without some a priori reason for suggesting that repetitions and changes are equal, the argument goes better in the other direction. That is, if RT does not increase with N, but the proportion of repetitions does, then repetition RTs must equal non-repetition RTs whatever underlying processing model is postulated.

In short, these models may handle tasks with different individual Bs, but they are not designed for tasks in which $B = 0$.

5.2

There is a second important area which existing models do not cover, namely the effects of latent stimuli. As defined in Chapter II, on any trial the latent stimuli are those which are alternatives in the task but which are not the one presented. Kornblum (1965) showed that RT for a particular stimulus and response was affected by the nature of the response called for by a second (latent) stimulus. A similar conclusion can be drawn from the results of experiment 3. This effect is also clear in the independent results of Duncan (1977) and Smith (1977). Both compared RTs from two classes of task. In one class, ("unmixed" tasks), the association between each stimulus and its response was the same for all possible stimuli. In the other class, ("mixed" tasks), half of the stimuli had one association with their responses and the other half, another. Again comparison showed that the RT for the same S-R pair differed between the unmixed and mixed tasks, i.e. the latent stimuli affected the RT. The results of Smith (1977) will be given here in some detail as the model was developed to account for the pattern apparent in them. (A copy of this paper is included in Appendix 4). Differences between these results and those of Duncan (1977) will be discussed in Chapter VI.

Smith (1977) used the VT apparatus described in Chapter I with 12 subjects doing various combinations of the 6 tasks involved in the procedure. These tasks were labelled T1 to T6. The basic difference between them was the stimulus-response associations for correct responses. Three types of mapping were used:-

1. *Compatible*: Each stimulus had to be responded to by pressing the key under the finger stimulated.

2. *Reflected:* The same finger on the other hand was correct; for example, a stimulus to the left index finger was responded to with the right index finger. The stimulus-response mapping was a reflection about the body midline.

3. *Shifted*: The correct response was described by shifting the stimulated position to the other hand and responded with, for example, the left index finger if the right little finger was stimulated.

The fingers, the stimuli to them, and responses by them are labeled 1-8 from right to left and referred to in this way.

The tasks in terms of their mappings were:

T1: all compatible;

T2: all reflected;

T3: half reflected, half compatible; that is, a left-hand stimulus had to be reflected to give its correct response, and a right-hand stimulus had to be responded to with the stimulated finger;

T4: all shifted;

T5: half shifted, half compatible. Again, left-hand stimuli had to be shifted and right-hand stimuli were compatible with their correct responses; and

T6:

T6 was described in Chapter I, and measured RT when subjects made their responses in a predetermined sequence although the stimulus sequence was random, i.e. under conditions of stimulus uncertainty with response certainty. As mentioned previously, this task provided evidence that the compatible latencies from T1 were at some minimum level. Degree of choice (N = 2, 4 and 8) for T1 - T5 was varied as a within subjects factor. The comparisons of interest were within the trios T1, T2, and T3, and T1, T4 and T5, i.e. each mixed tasks with its constituent two unmixed tasks. Since the pattern of results is the same for each trio, only those from T1, T2 and T3 are given here. Firstly, the overall mean RTs were in the order $T1 < T3 < T2$. Comparing the stimuli with the compatible association in T1 (unmixed compatible) and T3 (mixed with reflected) revealed that RTs were longer in the mixed task. That is, the presence in T3 of latent stimuli with a more difficult association increased the RT on trials with the compatible S-R pairs. The equivalent comparison for the reflected stimuli, on the other hand, showed that RTs were <u>shorter</u> in the mixed task. That is, the presence of latent stimuli with an easier association decreased the RT for reflected S-R pairs. The third comparison, between the different associations in T3 showed that RTs to reflected S-R pairs were longer than the RTs for compatible S-R pairs, so the particular S-R association called for did influence RT. These three points held for 2, 4 and 8 choice conditions. Clearly the presence of latent stimuli with harder response associations increases, and with easier associations decreases RT. Interestingly the size of this increase or decrease was proportional to *log N*. A theory postulating a simple constant-duration decision of "which association" to use for the given stimulus is obviously inadequate to account for these data, but the model detailed below can.

5.3 A third consideration in developing a new model arises from the review in Chapter III. In view of the conclusions on the doubtful utility of assuming stages of processing, it seems opportune to attempt to develop a stage-free or parametric model.

In consideration of these points, the model presented in section 6 is designed to cover the following areas.

(i) RT is proportional to $log\ N$ in general except that the slope relating RT and $log\ n$ can be zero (i.e. RT is independent of N) for some tasks.

(ii) Whole-task effects. In general it is not sufficient to consider the RT of one S-R pair in a task as an index of processing since it is affected by other aspects of the task. In particular, latent stimuli will increase RT if they involve a more difficult S-R association and decrease it if they involve simpler ones.

(iii) Response-related effects. One element of this is the temporal uncertainty of each response as shown in experiment 3. Speed/accuracy tradeoff is another aspect of response-related effects which should be covered.

(iv) Stimulus-related effects. The physical similarity between the stimuli affects the stimulus discriminability which in turn affects RT. Global stimulus probabilities control response probabilities and affect RT - stimuli with high probabilities have shorter RTs than those with low. Both of these points should be incorporated in the model if possible.

(v) Sequential effects in which a trial calling for the same response or using the same stimulus as the previous trial usually has a shorter RT, are important. Smith (1968) reviewed this effect and concluded that this was affected more by response than stimulus repetition. The main effect of repetitions can therefore be assigned to a response-related parameter.

(vi) Assumptions involving the existence of stages should be avoided.

6. A NEW MODEL

6.1 The model described here is a development of that presented previously by the author (Smith 1977). The style of the model is strongly influenced by a perceptual recognition model developed by Vickers (1970), and is also related to La Berge's model (section 3.4) with *TI*s replaced by accumulating evidence as in Vickers' model.

In this accelerating cycle model, evidence from each of the N possible stimuli (in the form of internal stimulus excitation, being either "noise" or "signal plus noise") is transformed into excitation on the associated responses. This process continues until one of the responses accumulates a preset amount of evidence and is initiated. We define a "cycle" as a segment of time in which one unit (arbitrarily small) of total stimulus excitation is transformed into the corresponding responses. Since latent stimuli affect RT, each stimulus has a share of the time in each cycle as detailed below. The basic time taken to transform one unit of stimulus excitation, which is called the association time, reflects the strength of the association between that stimulus and its correct response. The association time is high for low compatibility and vice versa. In addition, it is assumed that cycle times get progressively shorter in successive cycles. That is, the more evidence that has been accumulated the faster the transformation; perhaps indicating increasing focussing of attention or dedication to the task, or increasing ease as transformation paths become better established - somewhat like a within-trial practice effect. It is this feature which gives the model its name.

The contribution of each stimulus to a cycle is determined by two factors, its association time and its proportion of the total excitation. Access to the processor is shared between the stimuli in accordance with the proportion of the overall excitation represented by each stimulus, as in the example below. Once a stimulus has access, it will occupy the processor for the time needed to transform its excitation into its response, which is governed by its association time. Thus if there are 2 possible stimuli, S_1 and S_2, having 93% and 7% of the stimulus excitation, they will get 93% and 7% of the available access to the processor. In the case where the association times of the stimuli are 1 and 1.5 respectively, the basic cycle time will be $.93 \times 1 + .07 \times 1.5$, i.e. 1.04, if stimulus S_1 is given, and $.07 \times 1 + .93 \times 1.5$, i.e. 1.47 if S_2 is given.

The following is a mathematical development of the model consistent with this descriptive model.

6.2 Glossary of terms

The following terms are useful in describing the model and are defined together for convenience.

It should be noted that most of these have only a transitory role, in that they are not present in the final equations of the model, but make the exposition of the model easier. N and α, representing the number of alternatives and the S-R compatibility are the only parameters essential to the simple form of the model, with e and δ necessary in its extended form. The model therefore essentially has only 4 parameters.

1. N: the number of stimuli in use;
2. i: $i = 1,2, \ldots N$, a general stimulus set member;
3. j: the particular stimulus given on this trial;
4. k: $k = 1,2, \ldots N$, a general response set member;
5. m: the particular response made on this trial;
6. $r(i)$: a function specifying the S-R pairs of the task; for a correct response, $m=r(j)$;
7. $E(i)$: the initial excitation on stimulus i:
8. $e(i)$: the stimulus excitation. Scaled so that the total excitation is one unit;
9. q: the amount of excitation due to the signal:
10. u: the 'noise' excitation;
11. $\rho(k,t)$: the response excitation of stimulus k at the time of t;
12: $\alpha(i)$: the association time for the mapping from i to $r(i)$;
13: $\delta(k)$: the response firing level for response k;
14: s: a variable representing cycles through the process of translating e into ρ;
15: $t(s)$: the duration of cycle s.

We assume two sources of excitation exist; q, that due to the signal, and u, a measure of the neural and other noise unavoidable in the system. This noise is assumed to be independent of N and evenly distributed between the stimuli on average. That is, the greater N, the less noise on any one stimulus. It can be conceived as being inherent in the transformation mechanism and thus independent of N. It is possible that noise has a beneficial purpose, and is not merely a limitation of the system, as in the following explanation. The processor deals only with alternatives that have positive excitations, and ignores those with zero excitations. In this way, the noise in the system maintains the N stimulus representations or S-R associations since only non-zero ones have access to the processor and thus noise indicates which stimuli are possible. All other conceivable stimuli not in the current task are at the zero level and do not get a share in the processing.

At the onset of the stimulus, the initial stimulus excitations are

$$E(j) = q + \frac{u}{N}$$

$$E(i) = \frac{u}{N} \quad i \neq j \qquad 4.2$$

We can adopt arbitrary units for E, but for clarity in the following equations, it is simplest if we replace the Es with scaled excitations, $e(i)$, so that $\Sigma e(i) = 1$, i.e. $e(j) = \frac{E(j)}{\Sigma E(i)}$. Thus in the initial cycle, one unit of stimulus excitation is transformed into response excitation, which by definition takes one cycle. An equivalent but cumbersome alternative would be to replace all occurrences of $e(i)$ with $E(i)/\Sigma E(i)$. We shall return to this point later.

Every possibility gains access to the translation mechanism in each cycle, changing $e(i)$ units of excitation from stimulus to response excitation and in doing so adds to the cycle's duration in proportion to its association time, $\alpha(i)$, and its excitation level, $e(i)$. Less compatible S-R associations take longer as does the given stimulus (signal) relative to the latent ones (noise). The first cycle time equals $\Sigma\alpha(i)e(i)$, which is the sum of the individual alternative's times. As mentioned above, this process goes faster in each successive cycle, with the general cycle time at cycle s given by

$$t(s) = \frac{\Sigma\alpha(i)e(i)}{s} \qquad 4.3$$

That the time taken in a cycle should vary inversely with the iteration variable, s, has at least two possible explanations. One is that time taken in a cycle by the transformation of a stimulus into its corresponding response is proportional to the constant association time, and the level of stimulus excitation stored in short term store. It is suggested that this falls off with iterations, and is given by $e(i)/s$. This fits at least qualitatively the fall off in neural reverberatory circuits with time. This, together with the assumption that each stimulus is serviced in an iteration, gives equation 4.3.

A second approach is to link the α and $1/s$. Under this suggestion, the time to convert a unit of energy from stimulus into its response decreases with iterations within any trial. This would be like a within-trial practice effect; the task becoming faster as the neural pathways used become refreshed, more worn-in. Or, in attention terms, a gradual focusing of attention away from monitoring and other tasks and onto the translation process of that stimulus. Again, with each stimulus serviced in each iteration, this gives equation 4.3.

This process continues until response *m*'s criterion, $\delta(m)$, is reached, in say *x* cycles and the RT is the sum, or more properly the integral of the cycle durations. That is,

$$RT\ (j) = a + \int_1^x t(s)\ ds \qquad 4.4$$

where *a* represents any small nonprocessing delays, e.g. those associated with the stimulus level rising to detectability or with the time from initiation of the response to its being registered by the apparatus. Substituting for $t(s)$ gives

$$RT\ (j) = a + \int_1^x \frac{\Sigma\alpha(i)e(i)}{s}\ ds$$

$$= a + \Sigma\alpha(i)e(i).\log x \qquad 4.5$$

since the mathematical definition of natural logarithms is

$$\log y = \int_1^x \frac{ds}{s}$$

It now remains to find the value of *x*. For the latency to be proportional to $\log N$, *x* must be proportional to *N*. It is certainly plausible intuitively that *x* is proportional to *N*; a number of suggestions can lead to this. The simplest is that a constant amount of response excitation is allocatable on each cycle and that is shared equally between all *N* possibilities. This gives each $1/N$. However, this would have all responses reaching criterion together. A simple modification, weighting the $1/N$ with the stimulus excitation, corrects this, so that the increment in $\rho(i)$ is $e(i)/N$. Then at cycle s,

$$\rho(k,s) = \int_1^s \frac{e(i)}{N} \, ds$$

$$= \frac{e(i)}{N} \cdot (s-1) \qquad 4.6$$

So

$$\rho(m,x) = \frac{e(j)}{N} (x-1) \qquad 4.7$$

But $\rho(m,x) = \delta(m)$ by the definition of x. Therefore

$$x = \frac{\delta(m).N}{e(j)} + 1 \qquad 4.8$$

Returning to equation 4.5 and substituting for x,

$$\mathrm{RT}(j) = a + \Sigma\alpha(i)e(i).log\left[\frac{\delta(m).N}{e(j)} + 1\right]$$

$$= a + \Sigma\alpha(i)e(i).log\left[\frac{\delta(m)}{e(j)}\left(N + \frac{e(j)}{\delta(m)}\right)\right]$$

$$= A + B \; log\left[N + \frac{e(j)}{\delta(m)}\right] \qquad 4.9$$

where $A = a + \Sigma\alpha(i)e(i).log \dfrac{\delta(m)}{e(j)}$

and $B = \Sigma\alpha(i)e(i)$

As the response criterion $\delta(m)$ increases relative to the stimulus excitation, $e(j)$, the value of $\frac{e(j)}{\delta(m)}$ tends to zero, while if $\delta(m)$ and $e(j)$ are equal, $\frac{e(j)}{\delta(m)} = 1$.
We can assume that $\delta(m) > e(j)$, imposing the restraint that at least one iteration is needed to reach a response criterion, so that $e(j)/\delta$ ranges between 0 (low e, high δ) and 1 (equal e and δ): the model thus offers an explanation of why sometimes $log(N)$ and sometimes $log(N + 1)$ gives the better fit to experimental data. Low stimulus intensities

(or more likely, discriminabilities) should give a better fit against $log(N)$, while high intensities should be better fitted against $log(N + 1)$. It does in fact appear that the stimulus intensities used by Hyman (1953) whose results are well fitted against $log\ N$ were almost certainly less than those used by Hick (1952a) whose results are better fitted against $log\ (N + 1)$. For the rest of this work we shall use $log(N+D)$ where $D = \frac{e(j)}{\delta(m)}$.

The model also offers a partial explanation for the intercept, A, in equation 4.1. The given expression for A shows that part of this is inherent in the process, and is time dependent on $\delta/e(j)$, which is needed for a decision to be reached. It also gives the intercept as varying with α. It is suggested below that α will decrease with practice, and therefore so will the intercept. Teichner and Krebs (1974), in a review of 59 visual choice reaction time studies, conclude that the intercept does in fact decrease with practice, and moreover is a function of the stimulus coding required.

If δ is constant across responses - i.e. no concentration or other biases exist - equation 4.9 is independent of m. Hence the mean RT over all stimuli is given by

$$\mathrm{RT} = A + \frac{\sum_{j} \sum_{1} \alpha(i)e(i).log(N + D)}{N}$$

$$= A + \frac{\Sigma\alpha(i)}{N}.log(N + D) \qquad 4.10$$

as required.

6.3 Applications to this experiment

For an unmixed task in which the same S-R association holds for all stimuli, α will be independent of i, at least to a first approximation, and (4.10) becomes

$$RT = A + \alpha \log(N + D) \qquad 4.11$$

Thus an estimate of α for a particular S-R association is the slope of the regression line of $\log(N + D)$ on RT from a task using only that association. In addition, if $\alpha(i)$ depends only on the S-R association for that stimulus, we should expect that the same α would apply in a mixed task, as for the same association in an unmixed task. That is, for the mixed tasks described above, in which half the stimuli used one association and half another, the overall slope in (4.10) should be the mean of the two αs for the component S-R associations. The slope values calculated from the data in Table 4.1 for the compatible, reflected, and half reflected-half compatible tasks were 11, 125 and 75 respectively. The mean of the first two is 68, which is close to that of the mixed task. In addition, it would be expected that the calculated slope for a mixed task in which two stimuli map into each response as occurred here, would be lower than the simple mean of the αs incorporated in it, for $\rho(m)$ will have two increments (one signal and one noise) per cycle and so will reach criterion faster (lower x implies a shorter RT). This effect also occurred in experiment 3 as will be detailed below. Thus the result is acceptably near the value predicted by this model. An equivalent direct comparison for the other association, shifted, was not possible since some subjects who did the half shifted-half compatible task did task 6 instead of the compatible task so the relevant means came from different although overlapping subject groups.

TABLE 4.1: Mean choice RTs in msec for three related tasks, compatible, reflected and half reflected-half compatible as explained in the task. Each mean is taken over 196 trials from 4 subjects.

(From Smith 1977).

	N = 2	4	8
Compatible	227	240	248
Reflected	310	444	559
Half Compatible-Half reflected	204	266	353

According to this model the effect of latent stimuli is proportional to their αs, and their excitation levels, as can be seen from (4.9). Consider one subset of stimuli with the same association in two tasks. For example, let the left half of the stimuli have an association time of α_1, and the right half, α_2, in the mixed task. We shall use the notation that $RT_{x,y}$ is the mean RT for stimuli with association α_x when α_y is the association time for the other, latent, half of the stimuli. Then the difference between the mean RT for the stimuli with α_1 in the mixed case, $RT_{1,2}$ and the equivalent mean from the unmixed case, $RT_{1,1}$ is

$$RT_{1,2} - RT_{1,1} = u(\alpha_2 - \alpha_1)\ log(N + D) \qquad 4.12$$

from equation 4.9. This is positive if $\alpha_2 > \alpha_1$ (e.g. comparing reflected stimuli in mixed and unmixed tasks) but negative if $\alpha_2 < \alpha_1$ (e.g. compatible stimuli in mixed and unmixed tasks) and is proportional to *log N* which agrees with the result found.

Similarly the difference between RTs for different associations within a mixed task is given by

$$RT_{1,2} - RT_{2,1} = q(\alpha_1 - \alpha_2)\ log(N + D) \qquad 4.13$$

(where $RT_{1,2}$ is the RT when the given stimulus has an association time, α_1 and the latent stimulus has association α_2, and vice versa for $RT_{2,1}$), which is proportional to *log N* and shows that the stimuli with the larger α have the larger RT, again in agreement with the data from this experiment.

6.4 The model applied to Experiment 3

All relationships between the RTs from the tasks in experiment 3 follow from this model. The temporal uncertainty principle is realized by assigning higher ρs to responses with less regular occurrences, i.e. *T, B* and *C* than to regular responses, i.e. *A* and X_1. It takes longer to accumulate to a high ρ, i.e. high ρs give long RTs. Thus *A* and X_1 are less than *T, B* and *C*. In addition, the latent stimulus principle applies in *x, b* and *c*. The compatible VT response has been shown to have an α of zero, since RT in *b* does not increase with *N*, and so the effect of the latent stimulus in *b*, which is proportional to its α, will be zero. That is, it will have the same effect as no stimulus and no response. But this is what occurs in *t*. Hence *T* = *B*, as found.

The latent stimulus in *c* cannot have an α less than that for *b*, since α cannot be negative. Evidence reviewed in Chapter III was consistent with the view that it is indeed less compatible to ignore a highly compatible stimulus than to respond to it. That is, its α will be greater than zero, and it will increase the comparison RT, giving $B < C$. In addition, C will increase with the number of stimuli to be ignored, which is what Mowbray (1960) reported, when using a digit naming task.

For stimulus 1 in x, i.e. the compatible stimulus-response pair, $1 \rightarrow 1$, α will also be zero, but for the incompatible pair, $2 \rightarrow 1$, α will be greater than zero. This gives $X_1 < X_2$. The final relationship, between A and X_1 is more complex. On the basis of their ρs they would be equal. The task x involves a latent stimulus with $\alpha > 0$, and so X_1 should be lengthened. Counteracting this, however, both stimuli are being transformed into the same response, which therefore accumulates excitation from both the signal and the noise stimuli. This results in that response's criterion being reached sooner than if the signal alone contributes to it, as noted above in the unmixed task. This reduces its RT. Since the increase due to the latent stimulus compensates for the decrease due to two sources of stimulation for one response, the result $A = X$ is consistent with the model.

6.5 Other applications

In this section the points listed in section 5.3 are discussed in relation to this model.

(i) Under this model, RT is proportional to $log(N + D)$ where $0 \leqslant D \leqslant 1$ so its general form is in agreement with that area of results. Indeed, as noted above, the parameter D enables the two rival formulae of Hick and

Hyman to be reconciled. This point is tested further in experiment 7 presented in Chapter VII.

The slope of the relationship is given by $\Sigma\alpha(i)e(i)$, which reduces to α for unmixed tasks. In its current form this model is not designed to predict what value α will have in a given task, although consistency is apparent for the same S-R association in different tasks in that the αs found for two particular S-R associations in unmixed tasks can be used to predict the overall slope, B, in the compatibility mixed task, as discussed above. A task which shows no increase in RT with N like the compatible VT task in Chapter I, would have a measured association time of zero, which is not unacceptable in this theoretical framework, as it suggests that there is a complete association between the stimulus and its response and that no transformation is needed to convert the stimulus into its response. Given the directness of the relationship between a vibrating key and pressing that key, this is not implausible.

However, the introduction of latent stimuli with non-zero αs would induce a logarithmic increase with N in the RT even for stimuli with $\alpha = 0$, as shown in equation 4.10 and as found in this experiment.

The effect of practice in reducing the slope, B, can be accounted for. As subjects become more practised at a particular S-R association, that association becomes stronger. Hence its α will be reduced with its B, possibly to zero as Mowbray and Rhoades (1959) found. Indeed, the explanation of α as association time would support this approach by analogy with paired-learning tasks and would be similar to the suggestion made by Welford (1968) that with practice the associations between stimulus and response become built in as a kind of transformation table.

This explanation covers the results of experiments 1 and 2, in which adults rapidly attained an α of zero on VT apparatus, while children had larger βs and αs than corresponding adult values, reflecting their lesser experience in spatial identification and responding.

(ii) Whole task effects are satisfactorily handled by this model in its use of latent stimuli as detailed at the end of section 6.2.

(iii) Response-related effects can be mediated through the parameter δ. At the grossest level, getting the subject to concentrate on responses (set for responding) gives faster responses than if he concentrates on identifying the stimulus (Welford 1971). This could correspond to a lowering of δ or an aggregation of noise to that stimulus so that its excitation would be larger than usual, with an attendant decrease in x as in equation 4.8. Indeed, both mechanisms may occur together. Either possibility would result in more responses, correct and incorrect, being made with the speeded response. Such a response bias can be seen in the "2 choice with concentration on one stimulus" condition used by Welford (1971). The number of responses with the faster response was 309 (296 correct, 13 errors) as against 288 (284, 4) with the other. This large increase in the number of errors for the faster response was not found in the 4 and 8 choice.

A decrease in the specificity of the stimulus needed to make a response is often noticed when subjects adopt a bias towards quick responding. In extreme cases subjects waiting for a visual stimulus will respond to a loud sound. This suggests that the processor takes any extraneous stimulation and assigns it to the favoured response, i.e. treats random excitation or noise as belonging to that response, and hence more frequently responding in error than is usual. If instructed to guard against such responses, but to respond quickly, subjects may compensate by raising their δ. This could account for the result reported by John (1966), where RTs in a Donders' *c*-task were longer the louder the stimulus to be ignored. That is, to avoid making errors of commission, they needed a higher δ in the loud stimulus condition than in the soft.

It was suggested in Chapter III that the different regularities of interresponse times for a particular response in experiment 3 were at least part of the reason for the pattern of RTs obtained for the various tasks, viz, the more regular the response, the shorter the RT. If we assume that in general a subject can prepare better for regular responses by reducing δ without making errors of anticipation as he might with irregular responses, these results follow from this model.

Speed/accuracy tradeoffs can also be accounted for via changes in the average response criteria, $\delta(k)$. If these are low, RTs will be short and it is more likely that the continuously varying noise will be large enough for an incorrect response to reach its low criterion before the correct response. This gives a higher error rate for low δs. Conversely, high criteria give long RTs and make it improbable that noise will be large enough for long enough to cause an error. The specific form of the relationship between the error rate and δ has not been developed and will be left for later research.

(iv) Stimulus related effects. As mentioned before unequal stimulus frequencies affect latencies, with more probable stimuli responded to faster than others (La Berge & Tweedy 1964; and others). This model handles this at least qualitatively if it is assumed that the $1/N$ in equation 4.6 is taken as a measure of some payoff function $p(j)$ for the stimuli. In the usual equal frequency choice task with no special instructions, all stimuli would have an equal payoff, $1/N$. If stimulus frequencies are unequal, the subject can obey the instruction to react as quickly as possible by changing this payoff to the probability of a signal. We can replace equation 4.8 with

$$x = \frac{\delta(m)}{e(j)p(j)} + 1 \qquad 4.14$$

where $p(j)$ is the payoff weighting given to stimulus j. This interpretation is reasonable in light of the explanation of equation 4.8 given above. Replacing equation 4.8 with equation 4.14 gives shorter response latencies for larger $p(j)$ as required.

The effect of stimulus intensity in which higher intensity stimuli give shorter RTs is explicable. As stated above, the $e(i)$ were scaled arbitrarily so that $\Sigma e(i)=1$. Consider the effect on $e(j)$ of increasing $E(j)$, the absolute stimulus excitation. In brief, as $E(j)$ increases, so does $e(j)$ to an asymptote of 1 as can be shown from equation 4.2, and thus x decreases, from equation 4.8. That is, fewer cycles are needed to reach criterion for the more intense the stimulus since more signal excitation is transformed each cycle. This in turn means shorter RTs which is consistent with experimental results.

(v) Some features of sequential effects often noted in choice reaction times can be fitted with another assumption. If we assume that the stimulus and response excitation does not reset to zero immediately after a trial, but decays slowly, then repetitions of the same stimulus or response will be responded to more quickly, being as it were primed. Similar although lesser effects will be noted for successive trials in which the stimulus and response are not repeated but are in some way closely related. For example, a response by a different finger but on the same hand, will be faster than one by a finger on the other hand (Kirby 1975). Also, long RSIs would give smaller sequential effects than would short RSIs, as has been found by Bertelson in 1961 and others subsequently.

(vi) Errors. Errors are made in this model either if one of the latent stimuli gets a large amount of noise or has a very small criterion which causes its response to reach criterion before the correct response does, or if the transformation mechanism uses a wrong association. The latter is hard to quantify and hopefully happens rarely in normal circumstances. Vickers (1960) has shown that error latencies in a two choice task are faster than those of correct responses under a model like this if the response criterion is very low, which corresponds to a high error rate.

For less error-prone performance, a higher δ is needed and error latencies are then longer than correct responses <u>with the same δ</u>. At first sight it would appear that the accelerating cycle model fails on the same test that Laming rejected La Berge's TI accumulator model. However, although δ has been treated as constant across trials, it almost certainly varies. Within a block of trials, those on which δ is low will have a higher proportion of errors than will other trials with high δ. That is, errors will occur predominantly on trials with low δs, and correct responses on high δ trials. Hence the comparison between error and correct RTs is not between trials with equal δs, and since low δs give short RTs, errors will usually be faster than correct responses if δ varies, even though they are slower than correct responses with the same δ. So simply releasing the unlikely restriction that δ is constant, allows the model to fit the observed result that error RTs are usually shorter than correct RTs. This argument applies equally to error versus correct RTs in La Berge's model, and suggests that Laming's (1968) rejection of that model was not wholly fair, since a less restrictive interpretation which could explain the results he found, was possible.

(vii) This model has avoided the assumption of stages as advocated in the review in Chapter III. Although it describes RT processing as a flow of evidence from stimulus to response, the flow is to be seen as embodying overlapping components, as favoured in the review in Chapter III. The degree of overlap may vary from complete to zero, depending upon the particular task, and so this model is not wholly inconsistent with a stage approach for some tasks. The accumulating process is that of a relative criterion model. Its viewpoint differs from similar models in that it considers equal amounts of evidence being accumulated in successively shorter cycles, rather than varying amounts of evidence being assessed in equal time slices.

It seems to cover a wide range of areas and to be capable of further extensions, for example in speed/accuracy tradeoffs or stimulus discriminability. It is an attempt to formulate a parameter model as an alternative to more conventional styles of model, as discussed in the review in Chapter III. Some of its assumptions and predictions will be tested in the following chapters.

CHAPTER V

MEASURING STIMULUS INPUT TIME AND NOISE IN CRT

1.1 Stimulus input time in CRT

Models of choice reaction time generally assume that the time taken to input a stimulus is independent of the rest of the processing, i.e. the input does not overlap the time taken for further processing, and that its duration is independent of the number of alternatives (Welford 1968; Smith 1968). Under the stage additivity hypothesis if the logarithmic increase in RT with the number of alternatives, N, is attributed to stimulus identification and response selection then the durations of other stages must be independent of or logarithmic with N or they will destroy the logarithmic relationship when summed with the two central states. As discussed in Chapter III, although the additivity assumption has been convenient from the viewpoint of modelling, it is not essential and produces difficulties in explaining the data presented in that chapter. Taylor (1976) has shown mathematically that alternative expositions are possible and cannot be ruled out on the basis of currently available data. That is, it is possible that any postulated processing stage may commence working on partial evidence from the previous stage without waiting for that stage to finish.

In particular this is so for the input stage which may send the evidence it has currently gained on to subsequent processing immediately or alternatively may forward evidence from stimulus samples built up over time as in most models described in Chapter IV. Allport (1968) showed that this evidence is most probably summarized from a constant duration back in time from the present. He presented ten horizontal lines one at a time on a cathode ray tube starting with the line at the bottom of the tube and working upwards. Although only one line was physically on at any time, if the rate of presentation was rapid enough, all ten appeared to be present simultaneously. If the rate of presentation was slowed down, nine lines only were seen at any one time. Each one of the ten will successively be missing and the missing line will move up the screen if the subject is taking samples of a constant duration, t msec, back from the present, since the missing line is the one which occurred more than t msec ago. This is what subjects reported perceiving. Regardless of which is more correct, a definite duration is needed for the overall process of inputting to produce sufficient information for a correct choice to be made. Any model of CRT processing starts with the stimulus as input to some system which transforms it into a response over time. It can be seen by tracing this process backwards from the response to the stimulus that the response is made on the basis of the stimulus entering the system over some duration, M msec, and that further evidence still passing in after M msec will have no effect. This holds whether the process is considered as serial or continuous. Trivially M is less than the RT, but how much so and how it is affected by N in choice tasks is less certain.

As mentioned above, serial additivity models assume that the duration of the input component of RT is either independent of N or logarithmic with N. This follows from mathematical considerations for if the overall RT is governed by

$$\mathrm{RT} = A + B\ log(N) \qquad 5.1$$

and the non-input stage durations, rt, are also logarithmic with N under the model,

$$\mathrm{rt} = a + b\ log(N) \qquad 5.2$$

then the input stage's duration, T, is found by subtraction. That is,

$$T = \mathrm{RT} - \mathrm{rt} = (A-a) + (B-b)\ log(N) \qquad 5.3$$

Hence T is independent of N (if $B = b$, i.e. the whole slope derives from non-input stages) or logarithmic with N. The simpler assumption that T is independent of N is usually made. Although M (the stimulus duration needed to produce a correct response) and T (the time to process M msec of stimulus evidence) are conceptually distinct, it is parsimonious and feasible to assume that at least T would be directly proportional to M, i.e. the time taken to pre-process M msec of stimulus information would be a multiple of M. This includes the case where T equals M and means that the relationship between T and N is of the same form as between M and N, while allowing the possibility that the time to input or preprocess stimulus information may exceed the stimulus duration.

The assumption that the stimulus input or preprocessing component is independent of N can be investigated experimentally. If it can be shown that increasing the duration of a stimulus up to some value, M msec, improves performance on the task, but further increases have no added effect, then it is reasonable to say that the input component needs M msec. That is, given a stimulus duration of M msec the subject achieves sufficient resolution of the display to perform as well as he will given unlimited viewing time, and this can be called the stimulus resolution time to distinguish it from the stimulus input time, T. It must be repeated that this does not guarantee the existence of stimulus input as a discrete serial stage of processing, since further processing may start while the stimulus is being gathered.

To measure M we need a technique that has the following 3 characteristics: (1) precisely controlled stimulus durations, (2) performance reaching a distinct (non-arbitrary) asymptote on a dependent variable, (3) freedom from confounding with N. Obviously if any one of these is not met, the resulting value of M may be challenged.

If a visual signal is presented for say x msec and then simply terminated, it remains available in some form, for further processing (Kahneman 1968). This persistence beyond the stimulus duration can be removed by presenting a second stimulus in the same location as the signal stimulus, destroying or masking the stimulus. Provided that the signal is on for a time sufficient to be perceived, its effective duration is approximately from the onset of the signal to the onset of the mask, regardless of its actual duration. This technique is called backward masking.

Fraisse and Blancheteau (1962) and Spencer (1971) have both investigated the assumption that stimulus resolution time is independent of N but reach opposing conclusions. Fraisse and Blancheteau, using CVC syllables in sets with N between 2 and 15 concluded "that recognition threshold is a function of the amount of information transmitted", i.e. proportional to $log(N)$. However the method they used makes their conclusion questionable. To assess the threshold at each degree of choice, subjects were shown each stimulus first for 6 msec, then 12, 24 and so on until they reported it correctly. This method does not meet the requisites noted above since there was no backward masking to control the stimulus duration, and the same stimulus was given repeatedly until it was identified, allowing integration of evidence between successive viewings. The measure is also confounded with N. Consider the case with $N = 2$. If the subject guesses wrongly at 6 msec, then he knows it must be the other response, even without the 12 msec viewing. In general, repeating the same stimulus on successive exposures means that the subject's choice set is reduced by one with each wrong guess, so that the task is truly an N choice only at 6 msec - at 12 msec it is an N-1 choice and so on. It is hardly surprising that the threshold increased with N.

In a methodologically better study, Spencer (1971) concluded that stimulus resolution time was approximately 125 msec, and independent of N. He measured the probability of correct response p_c, in blocks of trials with different stimulus onset asynchronies (SOA), for N = 2, 8 or 24 single letters presented tachistoscopically with a backward mask. In a pre-experimental session the stimulus duration needed to give approximately 85% correct recognition on a block of trials without backward mask was estimated for each subject, and this stimulus duration was used in the subsequent experimental sessions. This attempted to ensure that the asymptote was the same (85%) for each subject and each *N*. Analysis of the results showed that measured p_cs at all SOAs less than or equal to 100 msec were significantly different from the no-mask asymptote, while for SOAs greater than or equal to 125 msec they did not attain the .05 significance level. It should be noted however that a non-significant difference is only weak evidence of equality. The same result was found after the data was corrected for guessing, which was done to lessen the confounding of p_c with *N*. This correction compensates for the difference in the chance of correct response for different *N*, e.g. at zero SOA subjects must guess, and will get 50% for $N = 2$, but only 12.5 for $N = 8$, and this bias in favour of low *N* will hold, to a lesser extent, for longer SOAs. However, the stimulus used in this experiment were letters, for which RT to identify and name is itself independent of *N* (e.g. Morin, Konick, Troxell & McPherson 1965). Consequently it could be argued that finding that stimulus resolution time is independent of *N* in such a task should not be generalized to the more usual task in which RT is a function of *N*.

The experiment reported here investigates stimulus resolution time for $N = 2$, 4 and 8 in a lights-keys choice reaction task for which RT is proportional to $log(N)$, (Welford 1971). Rather than using p_c as the dependent variable, percentage of information transmitted will be used as this is free of confounding with *N* as discussed later.

1.2 Perceptual Noise

In addition to measuring stimulus resolution time, we can look at the perceptual "noise" in a choice reaction task. Since Hick (1952a) used Shannon and Weaver's mathematical theory of information transmission to describe human choice reaction processes, it has been common to consider subjects as being 'noisy' information channels. Subjects are seen as sampling the physical stimuli, taking samples made fallible by noise unavoidable in the nervous system. The more noise in the system the more variability is imposed on the true signal. Such models are usually applied to perceptual recognition tasks, such as in Vickers, Nettelbeck and Willson (1972), which contains a very clear account of the underlying theory. In brief, Vickers had developed a model in which a subject can lessen the effect of noise by taking multiple samples over time and accumulating the evidence in favour of each alternative until one reaches a preset criterion. The corresponding response is then made.

When presented with 2 discriminanda, e.g. a variable line of length X and a comparison line of length Y, the subject takes successive samples, x and y, of their lengths. It is assumed that x varies from sample to sample as it is distorted by normally distributed random noise, but has a mean value of X. The subject then adds all negative $x-y$ differences to an accumulator for the response "$X < Y$", and all positive $x-y$ to one for "$X > Y$". Whichever accumulator reaches its present level first determines the response made, and the reaction time reflects the accumulation time. If the difference $X-Y$ is large, relative to the variability induced by noise, the response will be fast, since the subject is accumulating large x-y values, and accurate, since accumulations into the incorrect response, from noise, will be small. At the other extreme, with X just greater than Y, responses will be slow (many accumulations of small differences) and inaccurate (contributions of noise will be about the same as the signal). Thus performance ranges from fast and accurate for large differences to slow and inaccurate for small differences. The proportion of "$X > Y$" responses is given by the proportion of x-y differences greater than zero (Vickers et al. 1972) which is determined by the ratio of the parameters of the normal distribution of x-y, namely the mean, X-Y and the variability, or noise. That is, p_c is a function of the signal-to-noise ratio. If noise is normally distributed the psychometric curve of p_c versus stimulus magnitude will ogival (which is the result found by Vickers et al. 1972) and we can take its variance or equivalently its standard deviation, σ, as a measure of noise. Strictly speaking, σ is a measure of the signal-to-noise ratio, but in the experiment reported here, signal strength can be taken as constant. In this case, σ will depend only on the magnitude of the noise, and we can refer to σ as noise, for the sake of brevity.

By accumulating over time, subjects are effectively reducing the variance of the stimulus evidence, i.e. increasing the signal-to-noise ratio and hence increasing p_c. It follows that the greater the noise the more samples are needed for a subject to achieve any p_c level for a given stimulus magnitude. To take more samples of the stimulus, more time viewing it is required. In backward masking studies the information is removed from the display as soon as the mask appears so the subject can only sample noise, and the time during which the subject can sample the stimulus can be precisely controlled. Thus the greater the noise the more samples of the stimulus, i.e. the longer the SOA needed to overcome its effect, and reach asymptotic performance. Since increasing the stimulus magnitude viewed for a set time is equivalent to increasing the viewing time of a constant stimulus magnitude, we can assess the magnitude of the noise, relative to that of the stimulus, by estimating σ from the ogive of p_c measured at a range of SOAs.

Choice reaction can be considered as a limiting case of the perceptual recognition paradigm in which the subject is given unlimited viewing time (Smith 1968). Adopting this approach, we can extend the argument set out above to CRT and take the standard deviation of p_c versus SOA as the measure of noise in choice reaction tasks, and assess the effect of N on noise. Green and Swets (1966,p.64) characterize two-choice tasks as requiring the subject to distinguish one signal source from one noise source, while a three-choice task involves one signal and two noise sources. That is, noise should increase with N, since more alternatives means more noise sources and more overall noise. An alternative suggestion is given in the accelerating cycle model which assumes that noise is not dependent on the number o possible stimuli, being equal for all N. That is, the noise is added internally as a feature of processing the stimulus and is not directly associated with the possible alternatives.

The experiment described below measures the standard deviation of the psychometric curve for a range of N to see whether or not noise is a function of N in choice reaction tasks.

2. EXPERIMENT 4.

2.1 METHOD

Apparatus. The eight stimulus lights and response keys were those described in Chapter II, and the viewing distance was 2.5 metres.

On each trial, one light, the signal light, was switched on and then after one of ten different stimulus durations all 8 lights were illuminated, thus providing a backward mask - unless the subject had already responded. The ten durations, which were selected after running four subjects in a preliminary experiment, were 10, then to 135 in steps of 15 and 4000 msec. The mask (or the 4000 msec duration signal) stayed on until the subject pressed a response key, whether correct or not. The next trial was presented 1.5 seconds after the response key was released.

Reaction time was measured from the onset of the signal light to the first down-press of a response key. The display, timing and response recording were done by a PDP/8L computer.

Subjects. Nine subjects, 6 male and 3 female, aged between 18 and 25 and unaware of the experiment's purpose were run for one session each.

Procedure. Each session consisted of familiarization trials, followed by 2, 4 and 8 choice tasks, with order controlled in a Latin square design. The familiarization consisted of 64 trials in which the stimulus cycled from right to left as described in Chapter I , giving the subject practice in viewing the display and responding without practising the choice task.

A short break followed and the 2, 4 or 8 choice conditions were run. All subjects were asked to respond as fast and as accurately as possible as is usual in a CRT paradigm. They were told which subset of 2, 4 or all 8 lights would be presented in that condition. The 2 choice always used the central two lights (and keys for responses) and the 4 choice used the central four. Subjects kept one finger on each of the eight keys for all conditions, ensuring that response performance was constant across *N*. The mask was the same for all, that is, all eight lights came on. In the preliminary experiment, the mask used was only the subset of stimulus lights for that condition. However, induced motion was noticeable for the 2 choice and the 4 choice to a lesser extent with the duration of apparent movement away from the stimulus light. Vickers et al. (1972) also noted this in their experiment 1, for which only the shorter line was lengthened in the mask. As for them, changing the mask to reduce apparent motion had no relevant effect on the results. The eight light mask made apparent motion less noticeable and comparable for all degrees of choice. The subjects were told that on some trials they might respond before the mask came on (none did for other than the 4000 msec duration), and that if after the mask had appeared they were uncertain as to which had been the stimulus light, they were to make their best guess.

Each task consisted of ten practice trials, starting with an SOA of 180 msec and decreasing in steps of 5 msec. These trials were discarded and used only to accustom the subjects with the masking situation. This prelude was followed by 240 trials, with each stimulus and each SOA occurring equally often in blocks of 40 trials for the 8 choice, and 20 for the 4 and 2. In addition, each stimulus was presented an equal number of times at each SOA over the 240 trials. The trials with a stimulus duration of 4000 msec - essentially providing continuous viewing (*c-v*) until the response had been made - were included to measure the actual asymptote achieved in the context of the overall task, and to see how similar the task was to an unmasked choice reaction task.

The masking here is particularly simple and clearcut, thus avoiding some contentious issues. For example, whether feature detectors or template matching is involved in the central stages is irrelevant here, since the signal-nonsignal distinction is on one feature only, "on" versus "off". In this it differs from more structured symbols like letters. The difference between signal and nonsignal is large and so will be detected in one "inspection" or sampling period. It can be considered as a limiting case of the perceptual recognition procedure used by Vickers et al. (1972). The mask is also pure in that it removes all information about which signal was given by presenting all possible ones and does not rely on contrast effects. Finally, the task has as many responses as there are stimuli, rather than just two - "present" or "absent". That this is important has been shown by Rabbitt (1959), who presented evidence that the number of response categories is a major factor in response latencies.

3. *RESULTS*

3.1 *Information transmitted.*

TABLE 5.1: Information transmitted, in bits, at each SOA for N = 2, 4 and 8. See text for the explanation of c-v or continuous-viewing trials.

H_t*(bits)*

SOA(msec)	*N = 2*	*N = 4*	*N = 8*
10	.02	.07	.25
30	.34	.25	.62
45	.56	.65	1.14
60	.64	.94	1.47
75	.82	1.25	1.91
90	.80	1.31	2.18
105	.87	1.34	2.18
120	.96	1.50	2.33
135	.88	1.77	2.33
c-v (4000)	.96	1.62	2.47

A stimulus-response confusion matrix was prepared for each of the 10 SOAs and 3 degrees of choice from which the information transmitted, H_t, was calculated. The formula used was

$$H_t = \sum_i P_{i.} \log(P_{i.}) + \sum_j P_{.j} \log(P_{.j}) + \sum_{i,j} P_{ij} \log(P_{ij}) \qquad 5.4$$

where $P_{i.}$ is the probability of stimulus i, $P_{.j}$ is the the probability of response j and P_{ij} is the probability of response j being made to stimulus i. Using logarithms to the base 2, H_t is measured in bits. Table 5.1 lists H_t at each SOA for N = 2, 4 and 8. It appears that H_t increases linearly with SOA up to the achieved asymptotic value V, measured by the *c-v* trials. V is thus the maximum amount of information that the subject can transmit even given unrestricted viewing time. The equation describing this is

$$H_t = A + B.\ \mathrm{SOA};\ \text{or } V,\ \textit{whichever is the lesser} \qquad 5.5$$

To test the adequacy of equation 5.5 against the data, and to estimate the parameters A and B, a computer program was written to calculate the values of A and B for which the model specified in equation 5.5 gave the best least squares fit. These values are shown in Table 5.2, together with the asymptote and the SOA at which this is reached, i.e. the stimulus resolution time, M. The goodness of fit parameter, R^2, which equals one minus the sum of the squared differences between observed and predicted values divided by the sum of the squared observed values was .989, .989 and .995 for the 2, 4 and 8 choice respectively. These are quite near 1, showing that the equation 5.5 describes the data well. Since V, the achieved asymptote, varies with N (it must be less than 1, 2, and 3 bits for N = 2, 4 and 8 respectively) each H_t was expressed as a percentage of V. This was called P_t, and is plotted in figure 5.1, together with the best fitting line from equation 5.5 for the pooled data. Table 5.2 gives the parameters of equation 5.5 using P_t instead of H_t.

It appears then, that subjects do input information at a constant rate during brief exposures of the stimulus.

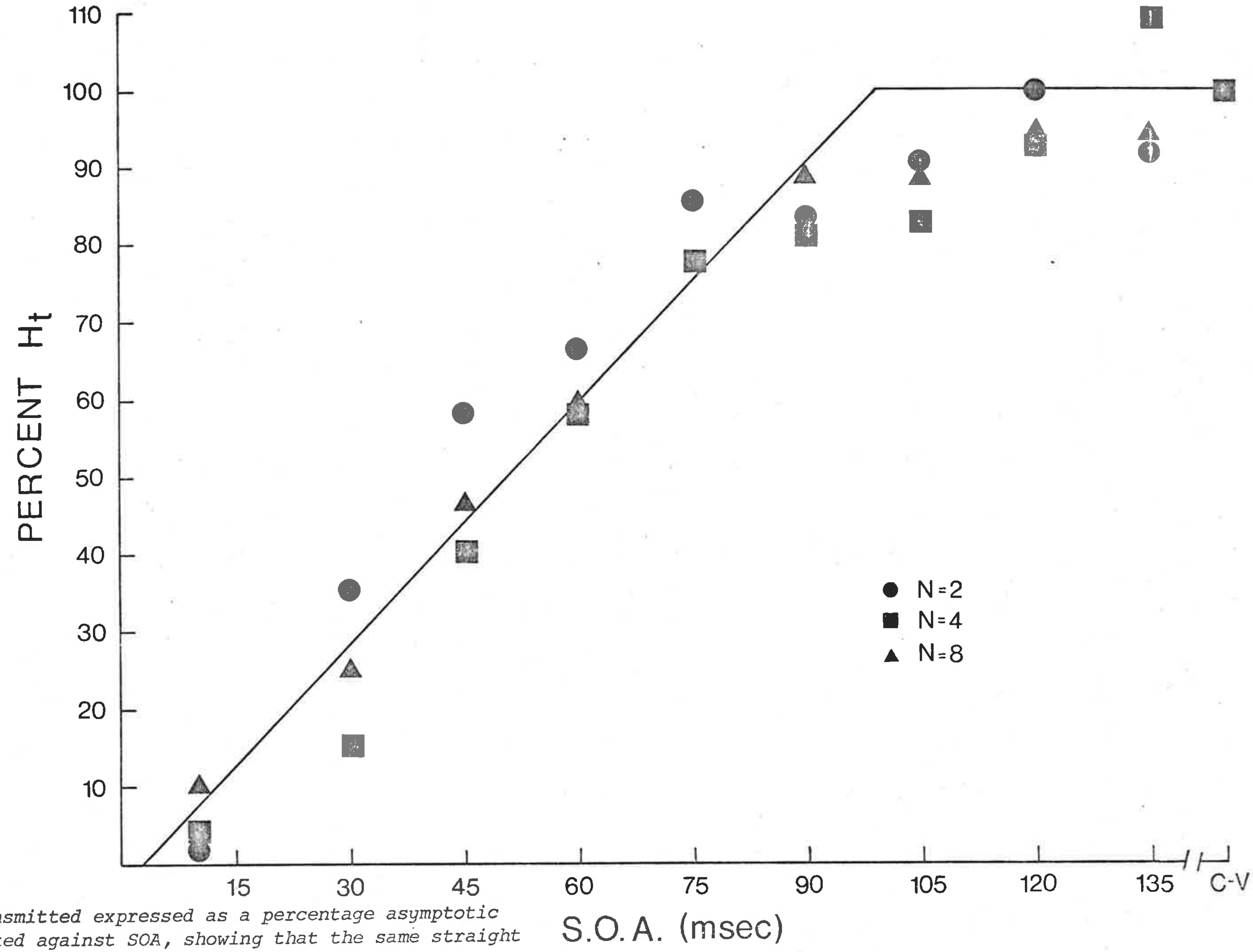

FIGURE 5.1:
Information transmitted expressed as a percentage asymptotic c-v value, plotted against SOA, showing that the same straight

TABLE 5.2: Parameters of the best fitting model of linear increase to asymptote, i.e. the lesser of A + B.(SOA) and asymptotic value at c-v.

a) for H_t, information transmitted, with N = 2, 4 and 8. Note that asymptotic performance is reached at about 100 msec for each N.

b) for P_t, percentage of asymptotic information transmitted with N = 2, 4 and 8. Note that about 1% is input in each msec for each N.

	N	Intercept A (bits)	Slope B(bits/sec)	reaches asymptote of V(bits)	at M(msec)
a)	2	.00	10.2	.96	94
	4	- .06	15.1	1.62	108
	8	.00	24.6	2.47	100
	N	A(%)	B(%/msec)	V%	M(msec)
b)	2	1.5	1.04	100	95
	4	- 3.0	.93	100	110
	8	.0	1.00	100	100

3.2 Percentage correct

The percentage or correct responses was calculated for each SOA, taken over all 9 subjects. This is shown in figure 5.2. As found by Vickers et al. (1972) the 2 choice curve is well described by an ogive with a mean of zero. Obviously the mean cannot be zero for $N > 2$ since the mean corresponds to 50% correct responding, while the value at zero is chance responding. Nevertheless, the curves for $N = 4$ and 8 were also well described by ogives but with non-zero means. Only the rightmost position of the ogives are shown in figure 5.2. The section corresponding to the negative half is theoretically present also, but adds nothing to the description of the ogive since it can be calculated from the positive section. For each positive point

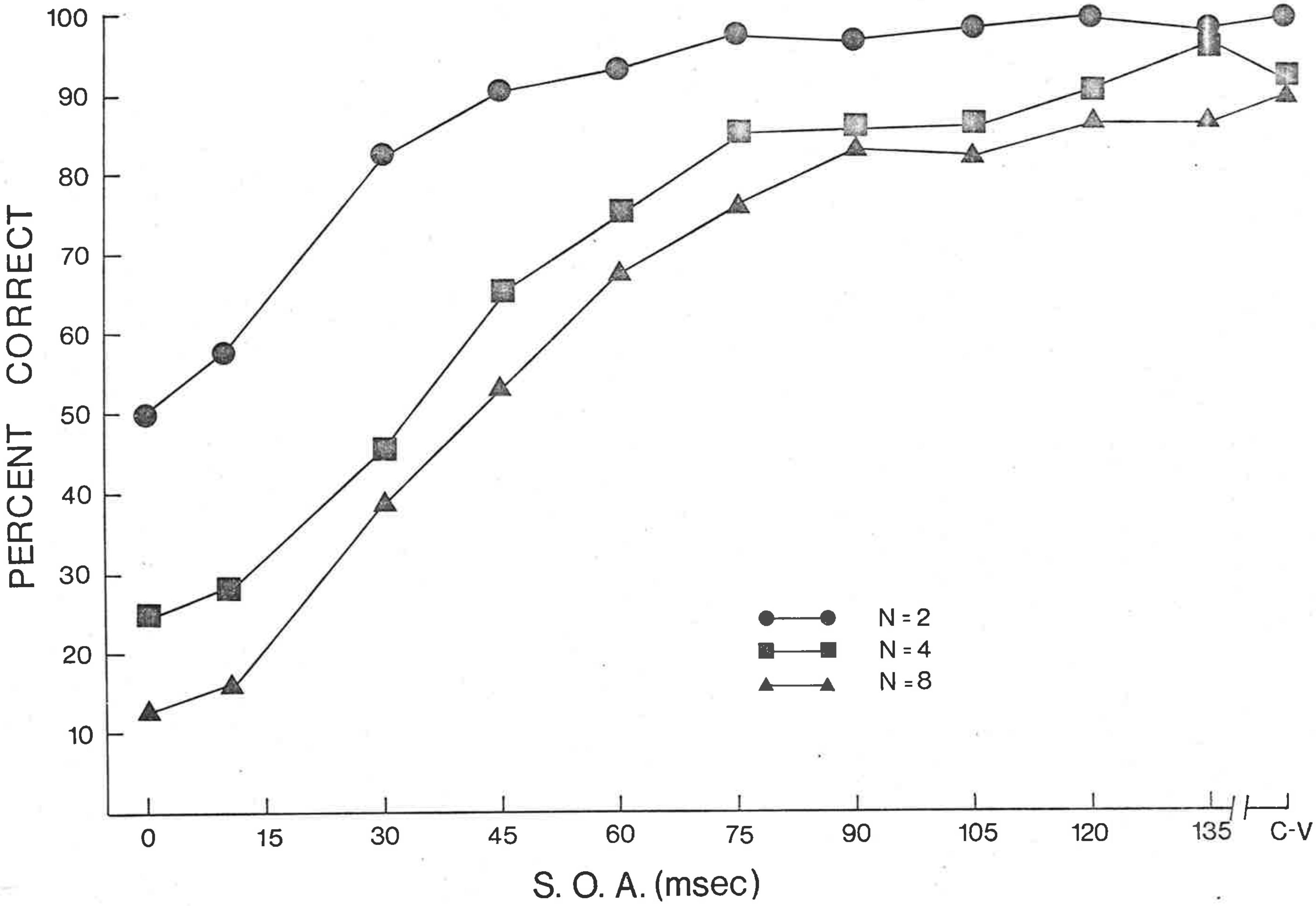

FIGURE 5.2:

Average percentage of correct responses as a function of SOA for N = 2, 4 and 8. Each curve is well described by an ogive with standard deviation of 35.

representing the percentage of correct responses per possible correct response, there is a corresponding negative point, representing the percentage of errors per possible incorrect response since this represents an effective negative duration of the incorrectly chosen response. That is, when stimulus 2 was given for 10 msec, followed by all 8, but the subject responded with response 3, the subject had identified the stimulus as number 3, which was on for -10 msec before the first light's onset. For the 2 choice, the value at the 10 negative points is just 100 minus the value at the corresponding positive duration. In the general case, this must be divided by the number of possible incorrect responses to give the percentage errors per possible error. For example, if $N = 8$, there are 7 possible incorrect responses which can be made on any trial. Thus, the ogive's values at "negative" durations are found by subtracting the percentage of correct responses from 100, giving the percentage of errors per seven possibilities, and dividing this by seven.

The results of calculating the mean and standard deviation of the best fitting ogive for $N = 2$, 4 and 8 are presented in Table 5.3. This was done in two ways. Firstly the asymptote of the ogives was set at the theoretical maximum, 100%, and the ogives fitted (Table 5.3a). The fit obtained was reasonable for $N = 2$, but very poor for $N = 4$ and 8 for which the asymptotic value was significantly less than 100. However when the fact that subjects make errors even on *c-v* trials is taken into account and the asymptote set to its measured value, better fits were obtained, as shown in Table 5.3b. R^2 for these fits were better than .99 for all three conditions. This demonstrates one advantage of including *c-v* trials in the procedure.

TABLE 5.3: Parameters of the best fitting ogive for percentage correct responses against SOA, with asymptote set at the theoretical maximum in (a) or at the measured asymptotic from c-v trials in (b). The goodness of fit as measured by the sum of squared deviations is given in the last column. In each case, using the measured asymptote gives a better fit. Note that the standard deviations in (b) are independent of N, which implies that the 'noise' is equal for such 2, 4 and 8 choice tasks.

	N	*asymptote*	*Mean*	*S. Deviation*	$\Sigma(o-p)^2$
(a)	*2*	*100*	*.00*	*35.8*	*40.1*
	4	*100*	*32.3*	*48.8*	*240.0*
	8	*100*	*45.4*	*52.2*	*430.0*
(b)	*2*	*99.5*	*.01*	*34.9*	*32.3*
	4	*92.1*	*28.1*	*35.4*	*58.0*
	8	*89.4*	*38.0*	*35.1*	*57.3*

3.3 Reaction time

It can be seen from figure 5.3 that overall RT decreased with increasing SOA when all subjects were considered together. This is as predicted by an optional stopping model in which the subjects must continue to

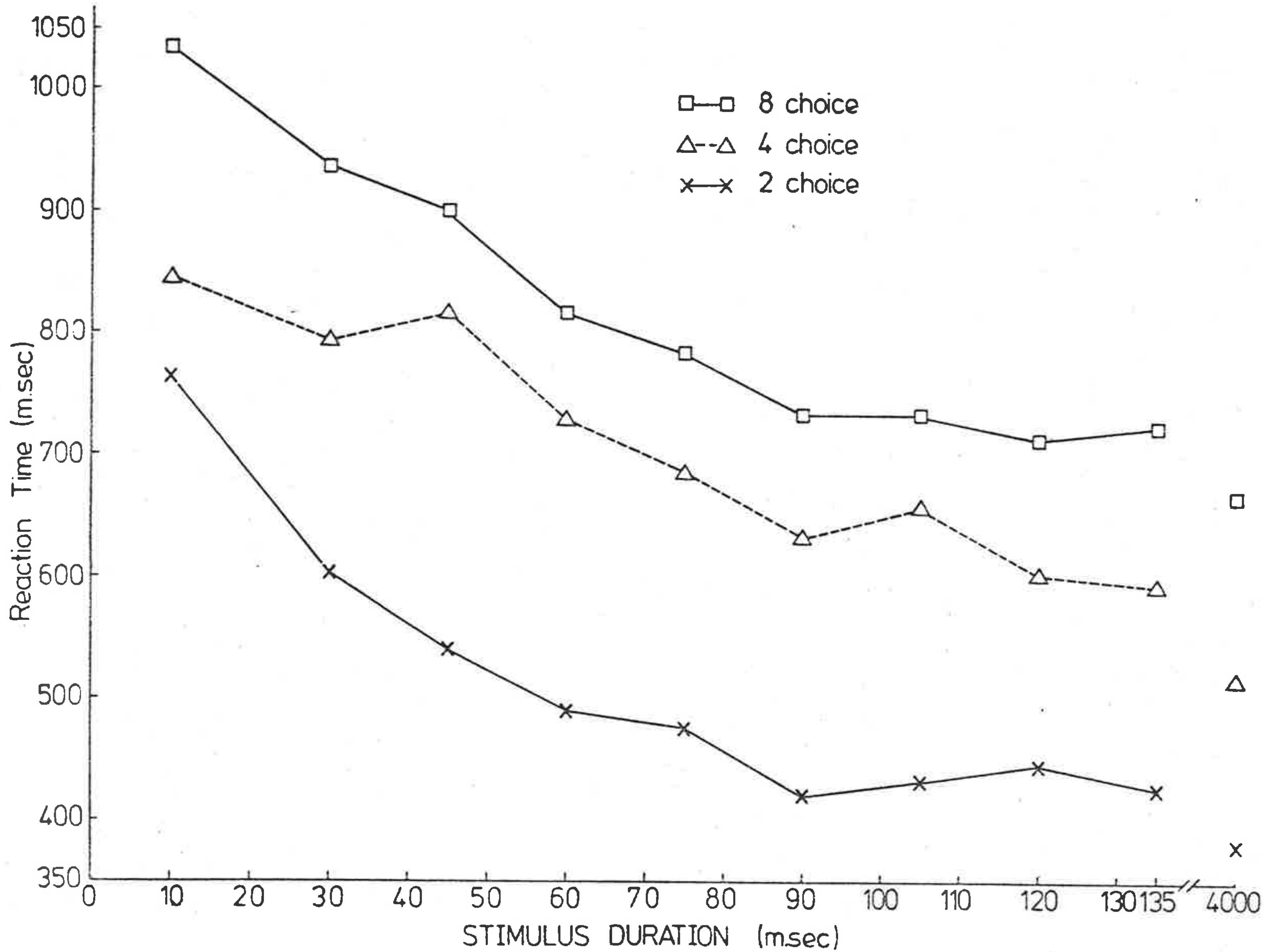

FIGURE 5.3: Mean overall reaction time from 9 subjects

accumulate sensory evidence even after it is masked (i.e. when the only sensory evidence available is noise), until a response criterion is reached. When subjects were analysed separately, 2 of the 9 did not show this pattern. For the other 7, analysis of variance showed that the effect of SOA on overall RT was significant at each level of N - as shown in Appendix 5A, 19 of the 21 F ratios had associated probabilities less than 0.1 - RT was negatively correlated with SOA (20 of the 21 Pearson r values were significant at $p = .05$) and error latencies were longer than correct - as shown in Appendix 5B the 21 unrelated t-tests had associated probabilities less than .05; all as predicted by optional stopping (Vickers et al. 1972). This pattern did not hold for S6 on $N = 2$, 4 and 8, nor for S9 on $N = 4$ and 8, for which RT was unaffected by SOA as shown by the following statistics. The probabilities associated with an SOA main effect ranged from .23 to .94 (see Appendix 5A); the corresponding correlations between SOA and RT were in the range -.08 to +.09 ($p > .2$ in all cases) and zero was in the 95% confidence of the slope of the regression line, RT on SOA. In addition, all unrelated t-tests for correct versus error latencies gave ps greater than .5. Indeed, 3 of the comparisons show errors are slightly faster than correct responses. These results are congruent with the subjects' adopting a temporal deadline response criterion and responding with the most favoured alternative after a set period of time. The length of this fixed sampling period is approximately the RT, which was on average 350 msec for S6 and 1050 msec for S9.

3.4 *Similarity to a standard CRT*

If we are to generalize conclusions from this task to non-masked lights-keys CRTs, the experimental results should have the known properties of CRTs. For example it is known from previous work with this equipment that overall RT is proportional to H_t and that in the 8 choice condition responses to stimuli adjacent to the edges of the display and the centre line ("outer" stimuli) give fewer errors and shorter RTs than the other 4 ("inner" stimuli) (Welford 1971). These features were also found here. The Pearson r between overall RT and H_t were calculated at each SOA, and r^2, the amount of variance accounted for by the linear fit, was greater than .82 for all but the 30 and 45 msec SOAs (.44 and .62 respectively). That is, RT is proportional to H_t at least for SOAs not less than 60 msec. For RT, a two way analysis of variance, SOA by stimulus position (inner or outer), showed that the main effects were significant ($p < .001$ for both), but the interaction was not ($p = .13$). The full AOV table is given in Appendix 5C. Thus it seems legitimate to consider this task as a valid form of CRT.

4 DISCUSSION

4.1 *Information input and stimulus resolution time*

In this experiment, information transmitted through the subject was a linear function of SOA, up to 100 msec at which it reached asymptote for N = 2, 4 and 8, as shown in figure 5.1. That is, the processing system inputs information from briefly displayed stimuli at a constant rate up to a maximum at a duration which is independent of N.

More interestingly, while for the overall process, time to respond, not rate, is a function of H_t, and its rate is a constant which depends on the compatibility between the stimuli and responses, the stimulus input rate is proportional to the maximum information transmitted in the task (which increases with N and thus the more information present, the faster rate it is input).

Indeed, the finding that all three degrees of choice reached asymptote at the same SOA (100 msec), indicates that all information which is going to be extracted can be input during this 100 msec, i.e. maximum resolution of the stimulus is achieved at 100 msec independent of N. This supports models of CRT in which only the more central processes of stimulus identification and response selection give rise to the increase in RT with N. This holds regardless of the function relating the input time, T, and the stimulus duration needed to produce a correct response reliably, M, for all functions will change equal values of T into equal M values.

This result offers an explanation of the intercept A in equation 5.1. Part of A may be attributed to T and be considered as the time needed to develop an internal stimulus image good enough to pass on to further processing. It must be reiterated that although this experiment can be interpreted in terms of a discrete input stage, the existence of such is supported but remains unproven. As noted in the introduction all models will at least imply that the stimulus must be present for a given time (here called M) for a correct response to be produced. Thus, the additional assumption that this time exists as a discrete stage, rather than a component, of processing is left open as there is nothing in this result from which we can gauge whether or not any other (more advanced) processing is ongoing during the stimulus resolution time. That is, the result is also consistent with continuous models such as the accelerating model, which do not assume the existence of inputting as a discrete stage. This test failed to distinguish between these types of model.

Whichever model is more correct, the result is interesting in that the stimulus resolution time is independent of the amount of information transmitted (at least up to 3 bits) Such independence may seem unexpected when considering people as limited channel information processors, but it is consonant with the research which has shown the existence of a 100 msec visual "perceptual moment" (reviewed by Kahneman 1968).

4.2 Perceptual noise

It was also found that the curves of p_c versus SOA for N = 2, 4 and 8 were each well described by an ogive with a standard deviation of 35 msec, but with means that increased with N. Inasmuch as noise, the moment to moment distortion in the stimulus or its processing, is reflected in the standard deviation of the psychometric curve as argued in 1.2, these results indicate that noise is constant in this task whether N = 2, 4 or 8. The assumption of the accelerating cycle model that noise is independent of N in these choice reaction tasks is thus supported as against that made by Green and Swets (1966) in which overall noise increases as a function of the number of stimuli.

The change in the means of the fitted ogives, which equals the SOA at which p_c = .5, with N is to be expected since an increase in the mean reflects a decrease in the value at the intercept, SOA = 0. This intercept is the probability of responding correctly by chance, i.e. $1/N$, and decreases with increasing N. This corresponds to moving the ogive to the right, increasing the mean as was found. So the change in mean is only a consequence of the decreasing change probability with increasing N with a constant standard deviation.

4.3 RT and SOA

As mentioned in section 3.3 seven subjects produced results which were clearly in support of an optional stopping model, in which the briefer the signal, the more noise without signal (the mask) must be sampled to achieve the preset response criterion level. As noise contributes only slowly to the response levels, it follows that the briefer the stimulus the longer the RT. Although the experimental design allows this evidence for an accumulator process to appear, it is a severe test, especially for higher degrees of choice. It is striking that it was passed for the data from 7 subjects. It is difficult to react quickly in a choice task while maintaining accuracy if the stimulus is only presented briefly. This is especially so for an 8 choice condition where the expected RT under continuous viewing conditions is about 550 msec (Welford 1971) for most of which time the stimulus in this experiment is masked. Thus it is not surprising that subjects may adopt a different cognitive criterion when faced with the difficulty of responding fast and accurately in such restricting conditions.

It is significant that the two subjects who showed no change in RT with SOA did so during their 8 choice and subsequent tasks. That is, S6 was given the 8 choice first, and his RT was unaffected by SOA for N = 2, 4 and 8, while S9 who did a 2 choice, and then the 8 and 4, only showed this different pattern for the 8 and 4 choice. This suggests that these two subjects adopted a different criterion for the 8 choice task and kept it for subsequent tasks. Kahneman (1968) has made the distinction between criterion level and criterion content: "content" is qualitative, applicable, inter alia, to the dimension on which the decision is made, and "level" is quantitative, indicating at what point in that dimension it occurs. The two subjects obviously did more than adopt a different criterion level, and the results suggest that the criterion content that they chose was to respond after a preset period. It is feasible that they still transformed and accumulated the evidence like the others, but made the response with the most evidence at the time the temporal deadline was reached. In any case their percentage correct data were little worse than the average, as the same number of errors or greater were made by 4 subjects at 2 SOAs, 3 subjects at 5, and 2 at the other 3 SOAs for the 8 choice, with similar counts for N = 2 and 4. S6 was one of the 2 fastest subjects while S9 was the slowest. That is, these two subjects adopted quite different levels within the deadline criterion. While it could be argued that S6 could afford to adopt this strategy without penalizing his performance on either RT or accuracy, this does not hold for S9 whose long deadline produced longer RTs than other subjects needed for equivalent accuracy.

There is nothing in the above discussion which suggests that this would apply in unmasked CRT tasks, for it is only in quite severe conditions that some subjects appear to break from the optional stopping criterion although having done so they carry their new criterion to subsequent tasks. We can therefore in general still consider the unmasked CRT process as involving an accumulator stopped by the first response to amass a preset amount of evidence, in the manner outlined in the accelerating cycle model.

5 CONCLUSIONS

Since the relevant features of the results in this task follow the expected pattern for CRTs as shown in it is reasonable to suggest that this experiment can be considered as a choice reaction task and the conclusions generalized to other such tasks, at least those with visual stimuli. Considered as a whole then, these results indicate that information is input from the stimulus display at a constant rate proportional to the amount of information in the task and this is done during a brief period, 100 msec in this case. At this SOA the stimulus resolution achieved is maximal regardless of N while complete processing from stimulus to response takes the subject a period proportional to the information extracted. That is, 100 msec is necessary and sufficient in this task to extract as much information as practical from the display for further processing. Secondly the unreliability of the overall processing system as measured by noise is independent of N. This suggests that noise is an attribute of the processing and not of the individual stimuli, for otherwise noise would be expected to increase with the number of stimuli. Finally, individual response criteria adopted in this task may vary, with most subjects using an optional stopping criterion, but others may respond to a temporal deadline.

CHAPTER VI

TWO S-R ASSOCIATIONS MIXED IN ONE TASK

1.1 INTRODUCTION

A major feature of the accelerating cycle model is its prediction of RTs for stimuli in a task involving two different S-R associations. Consider two tasks, A_1 and A_2, both of which have a single (different) rule, a_1 and a_2, respectively, governing the mapping of a set of 8 stimuli into 8 responses such that RT for A_1 is less than RT for A_2. If we now take four of the stimuli, say the left hand four, and assign them responses according to rule a_1 and assign the other four according to rule a_2, we create a new task, A_3, with a new overall compatibility and RT. Such tasks with two or more distinct subgroups of S-R associations will be called "mixed tasks". The model predicts three relationships, namely

(1) RT for those stimuli under rule a_1 will be less in A_1 than in A_3 which involves other less compatible S-R mappings.

(2) In A_3, RT for the stimuli under rule a_1 will be less than those under a_2.

(3) RT for those stimuli under rule a_2 will be greater in A_2 than in A_3 which involves other more compatible S-R mappings.

That is, it is not only the relationship between the given stimulus and its response which determines the reaction time, but also the other S-R associations latent in the task. Derivation of the specific relationships above from the model is given in Chapter IV.

Evidence in support of this was found by Smith (1977) for 2, 4 and 8 choice reaction times with a_1 as a direct spatial mapping and a_2 as either of two different spatial mappings and was summarized in Chapter IV. These results were open to criticism on two grounds. Firstly, mixing the two rules by applying a_1 to the left hand stimuli and one of the two a_2 to the right hand (Smith's task T3) created a situation in which there were half as many responses as stimuli, since the response to each stimulus on the left was made with a finger on the right as was each right hand stimulus. Thus mixing the mappings was confounded with a reduction in the number of responses which may have reduced RT for this a_2, giving relation (3) above. A further post hoc argument could explain relation (1): for example, by suggesting that a_1, a direct mapping with very compatible vibrotactile stimuli is in some sense automatic in the context of A_1 (all mappings direct) and that RT is raised rather than lowered as the above argument predicts as this automatic nature can no longer be used in a mixed task. Smith (1977) argued that this explanation, if true, would not be sufficient to cause the result found. Additionally, this confounding is not present for N = 2 and 4 with the other a_2 used for which the same pattern of results was found.

Secondly, the stimuli used were vibrations direct to the fingertips on the response keys. As mentioned above, this is a particularly compatible task when the response required is to press the key which vibrates which was the a_1 used as evidenced by the lack of increase in RT with N (Leonard 1959, and Chapter I). Hence the finding may not generalize to other stimuli. Perhaps this a_1 is so compatible as to be automatic in some sense so that subjects can direct all their attention to the less compatible S-R pairs and thus reduce their RTs to the less compatible a_2 stimuli and increasing those of a_1.

Two experiments were designed to clarify this; the first used vibrotactile stimuli with a_1 and a_2 chosen to avoid reducing the number of responses in the mixed task, and the second used visual stimuli to determine the effect of stimulus type on the relationships (1) to (3) above.

2. EXPERIMENT 5

2.1 METHOD

Subjects. Six men between the ages of 21 and 25 volunteered to act as subjects for the experiment. None had any previous experience in reaction time experiments and all were unaware of the purpose of the experiment.

Apparatus. The vibrotactile keys used in this experiment were as described in Chapter I.

TABLE 6.1: *The S-R associations for the three tasks are listed, showing which response was correct for each stimulus. The stimuli are numbered 1-8 from left to right, as are the response fingers, for description only and were not used in the experiment. The code describes each hand in the tasks distinctively and is explained in the text.*

STIMULI

	left hand						right hand			
TASK	1	2	3	4	Code		5	6	7	8
C	1	2	3	4	Dd	dD	5	6	7	8
T	4	3	2	1	Tt	tT	8	7	6	5
M	4	3	2	1	Td	tD	5	6	7	8

Procedure. Each subject's 8 choice reaction time was measured under 3 S-R associations in one experimental session. Table 6.1 gives details of the 3 tasks, D (direct), T (translated) and M (mixed). In D each stimulus was responded to with the finger that was vibrated, while in T the little finger was pressed in response to an index finger vibration, the ring finger to the middle finger, middle to ring, and index to little, on both hands. In M the left hand 4 stimuli were responded to under the translated rule and the right hand by the compatible rule. Thus the three tasks, D, T and M correspond to A_1, A_2 and A_3 in the introduction.

The order of doing the tasks was balanced between subjects. That is, the order for two subjects was DTM, for another two it was TMD, and MDT for the the third pair. The mappings were described to the subjects before each condition by detailing the appropriate response for each of the eight stimuli. The subjects were given 48 familiarization trials without being urged to respond quickly but responding according to the appropriate mapping to ensure that they understood the tasks. This was followed by the experimental block of 192 trials in which the subjects were asked to respond as quickly and accurately as possible. Within each block the possible 8 stimuli occurred at random except that each was given 6 times in the four quarter-blocks of 48 trials. The stimuli remained on until the first response, correct or not, was made, and the next stimulus came after a response-stimulus interval of 1 sec.

The delivery of stimuli, recording of responses and RT were controlled by a PDP/8 computer in the adjacent room.

2.2 *RESULTS*

A code which describes the different subtasks will be used to make the following discussion easier. Each hand under each task has a distinctive two letter code, one upper case and one lower case. The upper case letter is the first of the pair (leftmost) for a left hand stimulus and response, and on the right for a right hand stimulus. Each letter is either a "d" or a "t" for a direct or translated mapping respectively. Thus, tT refers to a right hand stimulus in the task where both left and right hands use the translated mapping, and Td refers to the left hand stimuli in the mixed task. The 6 subtasks are given in Table 6.1 and will be referred to as the different "conditions" in the experiment.

As discussed in the introduction, the model predicts that RT for the hands under the 3 tasks will be ranked

$$DD = dD < tD < Td < Tt = tT$$

That is, all direct responses are faster than all translated responses, and if the nonstimulus hand uses the direct mapping, RT will be less than if it uses the translated mapping. Figure 6.1 shows the mean RT for each finger in the 3 tasks with their error rates and shows that the ranking is as predicted. Furthermore this order was found for all 6 subjects (means and percentage correct data for each subject are given in Appendix 6).

Applying Jonkheere's test for average rank correlation with an external ordering gives a mean τ of 1, with a corresponding z score of 4.9 and probability $p < .0001$. The analysis of variance given in Table 6.2 (condition by finger by subject) showed that the condition and finger factors were both significant as was their interaction ($p < .0005$). It

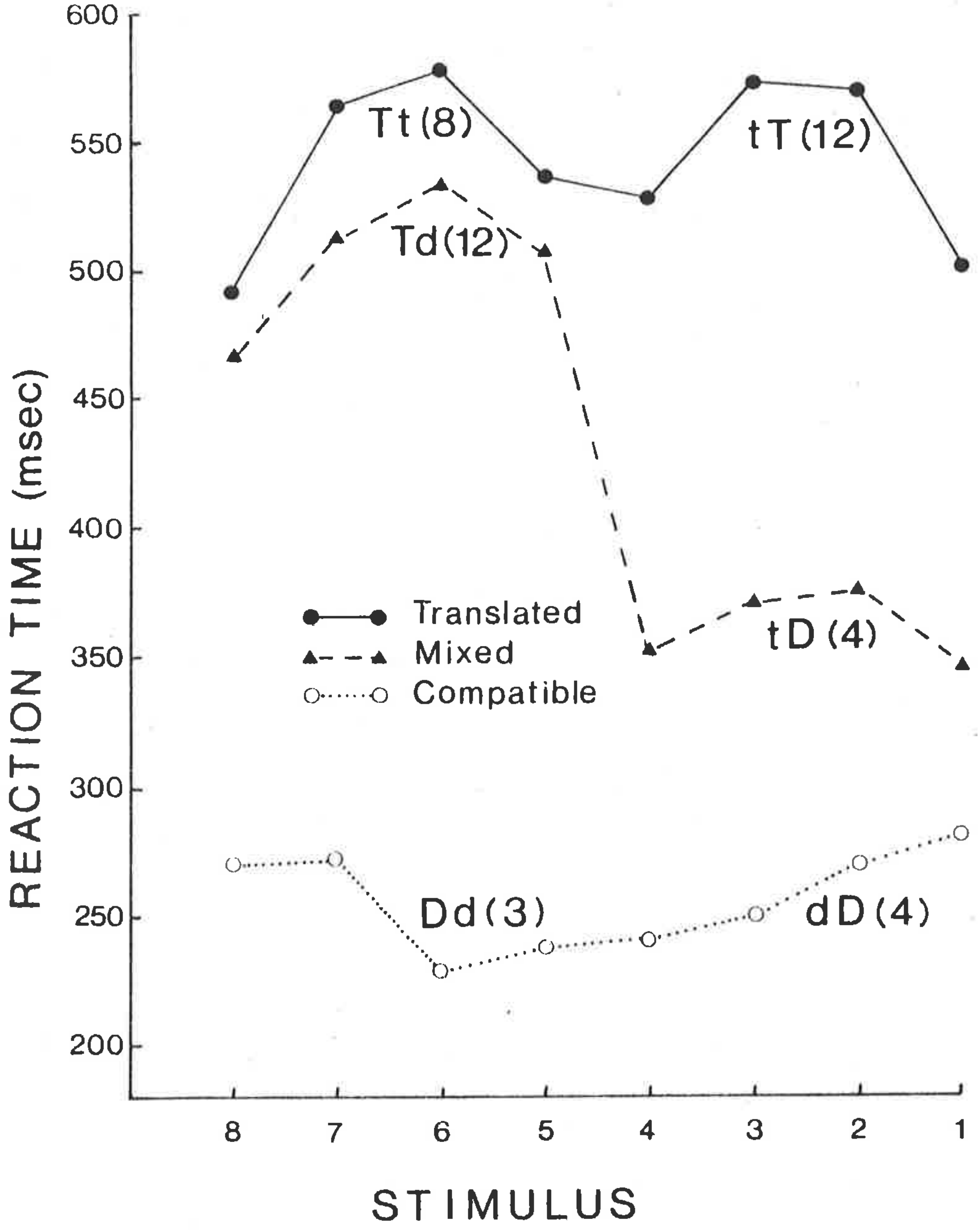

FIGURE 6.1: *Mean choice reaction times for each stimulus averaged over 6 subjects, each of whom did the three 8 choice tasks, Translated, Compatible and Half translated-Half compatible with VT stimuli. The numbers in parentheses are the error percentage for the left and right hand stimuli in each task.*

can be seen from Figure 6.1 that the ring and middle fingers are significantly slower than the little fingers for the incompatible tasks T and M (hence the significant finger effect) but not for C (hence the significant finger by condition interaction). The same results were found by Smith (1977) and are discussed in Chapter IV.

TABLE 6.2: Analysis of variance of correct reaction times from experiment 5 (vibrotactile stimuli) by finger (little, ring, middle or index) and condition (dD, Dd, tD, Td, tT or Tt) as explained in the text.

	df	Mean Square	F	p
Finger	3	11,304	11.3	.0004
Condition	5	450,032	176.4	<.0001
Subjects	5	162,478		
F x C	15	3,273	4.5	<.0001
F x S	15	1,007		
C x S	25	2,551		
F x C x S	75	729		

Planned comparisons showed that Dd and dD < tD, ($t = 2.8$, $df = 25$, $p < .01$), Td < Tt and tT ($t = 8.3$, $df = 25$, $p < .001$) and Dd, dD and tD < Td, Tt and tT ($t = 27$, $df = 25$, $p < .001$) which corroborates the conclusion above based on Jonkheere's τ.

2.3 DISCUSSION

The model successfully predicts the order of the RTs for the six conditions in this experiment which was the same as Smith (1977) reported, showing that the result was not an artifact of reducing the number of responses in the mixed task. The most important RT difference is that Td < Tt and tT, as the others can be explained easily if it is assumed that an additional stage is needed in processing a stimulus in a mixed task; namely to select which mapping is to be applied. This would lengthen RT and so account for the relationship tD > dD and Dd as found, but also requires that Td > Tt, which is against the data found here. With such a theory it could perhaps be argued additionally that Td was reduced from its predicted higher value by either a speed-accuracy tradeoff or by concentration on the Td stimuli. The former is unlikely, since the error rates for the three translated conditions, Td, Tt, and tT were 12%, 8% and 12% respectively. On the second point, if the subject concentrated on reacting most rapidly to the Td stimuli and considered the tD stimuli as secondary, the RT to Td would be reduced and tD increased (Welford 1973). On the concentration theory, it would be expected that the effect of concentrating on a particular subset would be equal regardless of the latent hand's S-R association i.e. that tD - dD would equal Tt - Td. This was not so, since tD - dD = 100 msec, but Tt - Td = 38 msec. A decrease in errors on the side concentrated on would be expected as a corollary, which was not the case.

TABLE 6.3: The S-R associations for the tasks used by Duncan (1977). The stimuli are numbered 1-4 from left to right, as are the response fingers. The Mixed-corresponding stimuli are 2 and 3 in Mixed-1, and 1 and 4 in Mixed-2. Mixed-opposite stimuli are 1 and 4 in Mixed-1, and 2 and 3 in Mixed-2

	STIMULI			
	1	2	3	4
Corresponding (Dd)	1	2	3	4
Opposite (Tt)	4	3	2	1
Mixed-1 (Dt and Td)	4	2	3	1
Mixed-2 (Dt and Td)	1	3	2	4

That this order of RTs may not occur for visual stimuli has been suggested by Duncan (1977). As stimuli he used a vertical line which could appear in one of 4 positions, 2 on either side of a central dot on a display screen. The subject responded by pressing the key appropriate to that stimulus. Duncan used three S-R associations, which he called corresponding, opposite, and mixed-corresponding or mixed-opposite. These are detailed in Table 6.3, and are equivalent to Dd, Tt and Dt or Td respectively in the terminology used here. Each task was described to the subjects by telling them that the stimuli were labelled 1-4, and the keys A-D, from left to right, and then listing the S-R pairs in these terms. For example, the "opposite" task was 1-D, 2-C, 3-B and 4-A. Thirty two subjects were used, 4 male and 4 female in each of the 4 conditions for one practice block plus five experimental blocks each of 144 trials. Comparisons between tasks were therefore also between different subject groups. Duncan found that the order of the mean RTs for the groups was Dd < Tt < Dt < Td. Accepting that the groups of subjects were homogeneous and that the results do reflect the pattern which would be found in a within subjects design, the results are against the model presented here. They are most simply explained, as Duncan does, in terms of an additional stage in the mixed tasks in which the subject decides which S-R mapping to apply. The data reported above for vibrotactile stimuli clearly do not follow that explanation, while Duncan's results with visual stimul are discrepant with the model argued for here. The next experiment was carried out to investigate this conflict by replicating the vibrotactile experiment with visual stimuli.

3. EXPERIMENT 6

3.1 METHOD

The methodology of the second experiment was identical to that described in experiment 5, with two exceptions. First, the stimuli were a horizontal row of 8 lens-topped neon lights described in Chapter II. The subject sat 2 m away at a table on which was the panel of 8 keys used in experiment 1. The vibrating rods were deactivated and instead of a vibrating stimulus one of the neon lights came on. None of the six subjects for this experiment participated in experiment !

The second difference was that subjects were run for 2 sessions each on different days.

3.2 RESULTS AND DISCUSSION

No clear pattern emerged on day 1. Three subjects gave mean RTs for the 6 conditions in the order expected under the model, but the pattern was different for the others.

The model was supported by the results on day 2, as can be seen from figure 6.2 which shows the mean RT for each finger in the three tasks together with the overall error rates. The predicted order was clear for 5 of the 6 subjects and for the sixth, Td was between, rather than less than Tt and tT (570, 568 and 572 msec respectively). Jonkheere's mean τ for this is 0.94 ($z = 4.6$, $p < .001$). The analysis of variance given in Table 6.4 (condition by finger by subject) showed that the condition and finger factors were both significant, as for the vibrotactile stimuli. Their

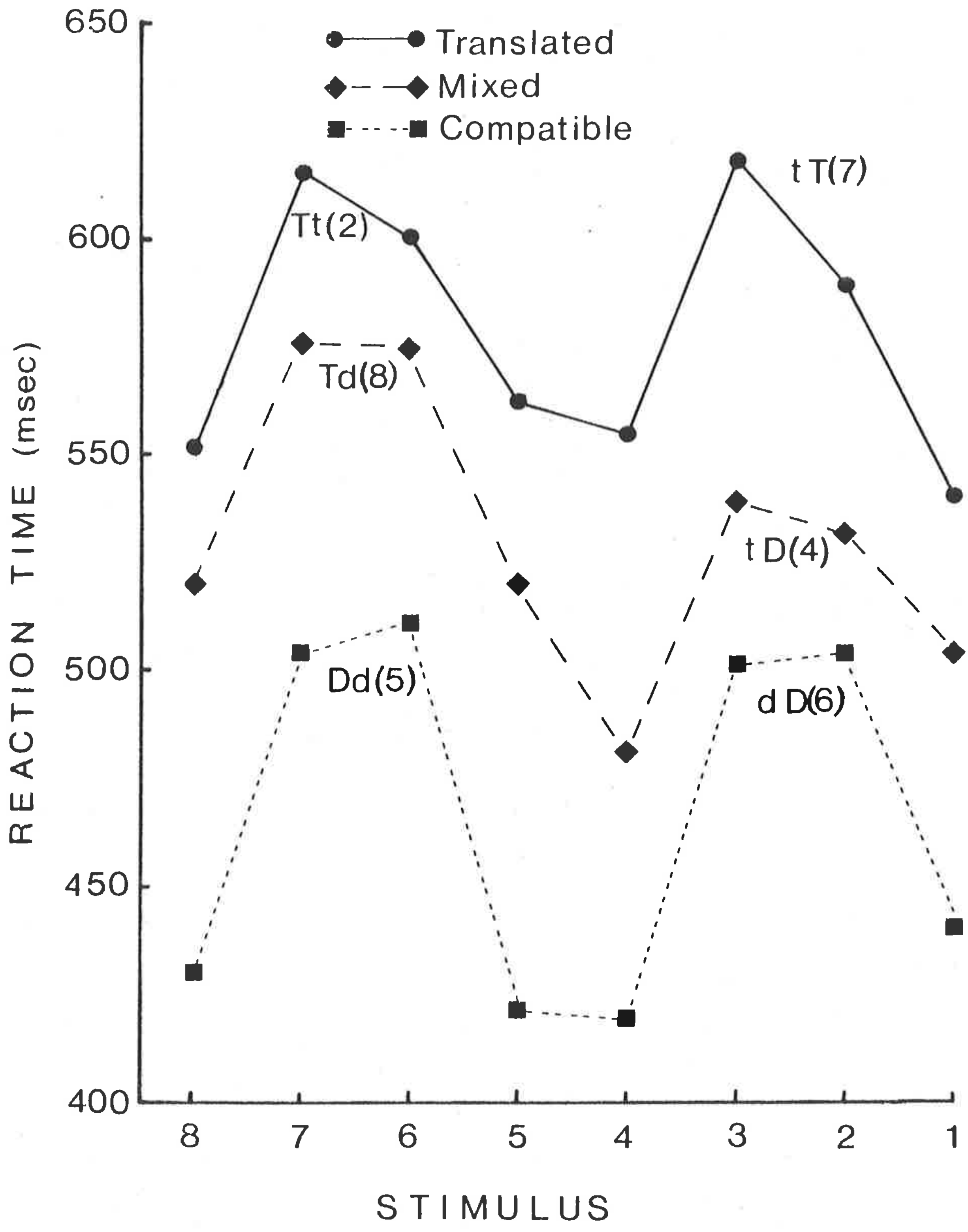

FIGURE 6.2: Mean choice reaction times for each stimulus, averaged over 6 subjects each of whom did the three 8 choice tasks, Translated, Compatible and Half translated-Half compatible, with lights as stimuli. The numbers in parentheses are the error percentages for the left and right hand stimuli in each task.

interaction was significant for the vibrotactile stimuli, but not for the visual stimuli. Comparison of figures 6.1 and 6.2 shows that the difference occurs in the direct task which has the expected finger effect (index and little fingers faster) for the visual stimuli but not for the vibrotactile.

Planned comparisons showed that dD and dD < tD ($t = 4.1$, $df = 25$, $p < .001$), Td < Tt and tT ($t = 2.6$, $df = 25$, $p < .05$) and Dd, dD and tD < Td, Tt and tT ($t = 13.2$, $df = 25$, $p < .001$) which corroborates the conclusion of the Jonkheere's mean τ test.

TABLE 6.4: Analysis of variance of correct reaction times from experiment 6, with visual stimuli.

	df	Mean square	F	p
Finger	3	52,227	37.6	<.0001
Condition	5	45,261	40.6	<.0001
Subjects	5	76,012		
F X C	15	1,251	1.7	.06
F X S	15	1,389		
C X S	25	1,113		
F X C X S	75	801		

Overall, the results from day 2 firmly support the model presented here and are in disagreement with the results and interpretation of Duncan (1977). That this was not so on day 1 suggests that an adequate degree of practice is needed before subjects perform as described by this model. For the highly compatible vibrotactile stimuli this can be achieved in one session while for the lights and keys it takes longer.

It seems likely that some feature of Duncan's procedure causes the subject to need additional time to recall which transformation is used for the given stimulus at least for the amount of practice given while subjects in the experiments reported here can do this with no time penalty, at least after 1 session's practice. There are two differences in the procedures which may have produced the discrepancy. Firstly the visual stimuli were different in kind. In this experiment the eight possible stimulus positions (i.e. the light bulbs) were explicitly on view at all times. Duncan's display contained no such explicit position cue, as each stimulus was displayed on its own, with the 4 possible locations defined implicity by the distance from a central fixation dot presented before each stimulus. The identification of one position from a display with all locations explicit is an easier task than with location information which must be extracted via some other variable like distance. The two experiments reported here together show that the harder the task, the more practice is needed before the subject settles into the pattern. Perhaps Duncan's results can be explained as being a more extreme case than the other two. That is the difficulty inherent in identifying his stimuli will increase the amount of practice needed for his results to conform to the predicted pattern found here. Some indication of this can be gleaned from his data as will be discussed later.

A second difference between the procedures concerns which subsets of the stimuli are assigned to each mapping in the mixed task. Here the two subsets were quite distinct, being the left half versus the right half, while Duncan split his 4 stimuli into the inner pair versus the outer pair. It seems probable that it is faster to decide whether the stimulus is left or right of centre than whether it is near or far from the centre, although this difference might disappear with extended practice. Interleaving the two subsets thus reinforces the argument in the preceding paragraph and suggests that a considerable amount of practice may be needed to overcome the two causes of stimulus processing difficulty and produce the predicted results.

Some indication that this may be the case is given by Duncan (1977,p.53). For the pattern he found, Dd < tT < Dt < dT, to become the pattern found here, Dd < Dt < dT < tT, both conditions of the mixed task must decrease. Duncan noted that Dt and tD were reducing faster than Dd and tT (the mean difference changes from 159 msec in trials 145-288 to 75 msec in trials 721-864 and appeared to be still decreasing), and may ultimately fit between Dd and tT. So it seems that his subjects were reducing the time needed to identify the stimulus and its subset (and hence its S-R associations) as practice increased. Duncan noted that the "data leave open the question of whether the difference would vanish with extended practice". The results found here suggest that it would be reduced to a large extent, at least for other, conceptually related,visual stimuli.

Thus the difference in results is explicable, but shows that this feature of the model should be applied carefully since it would seem that some situations introduce stimulus and mapping identification delays in responding in mixed tasks over and above those predicted by the model. Indeed these delays may be present in all mixed tasks but be small and disappear rapidly except if the nature of the stimuli or subsets is complex. That is, the model as it stands is incomplete in that there are factors influencing RT that it does not cover. It is more important at this stage to test other aspects of this version of the model against experimental data rather than apply an ad hoc patch to encompass Duncan's results. If further tests were to fail, the model should be discarded in toto, but if they succeed it can be retained as being adequate for a given range of situations. However, its partial failing for mixed tasks indicates that some refining is possible.

4. SEQUENTIAL EFFECTS

A subject usually responds faster in choice reaction tasks if the response or stimulus is the same as that for the previous trial. In this context, "the same as" can be measured on a range of criteria. The largest effect is found for a repetition of the identical stimulus (see e.g. Kirby 1975), but it is also found for the same finger on different hands - that is, if successive responses are made with different hands, RT is less if the previous response was with the equivalent finger (Rabbitt, Vyas & Fearnley 1975), and for successive responses with fingers on the same hand (Kirby 1975). It is the second case which is relevant here. The correct reactions for each subject were categorised as a repetition if the previous stimulus was to the same hand, and an alternation if to the other hand, and the mean RTs calculated. These are given in

Table 6.5. A four way analysis of variance (repetition/ alternation by hand by task by subject) on the results is summarised in Appendix 6, table C. Three tests were significant at the .05 level: the repetition factor ($F = 82$, $df = 1,5$, $p = .0003$), the task type ($F = 34$, $df = 2,10$, $p < .0001$), and the interaction of repetition and task ($F = 76$, $df = 2,10$, $p < .0001$). Thus, repetitions were significantly faster than alternations for both hands and all 3 tasks as expected, and RT was a function of the task's compatibility.

TABLE 6.5: Sequential effects in correct reaction times for the three tasks. The table shows the mean RT for left or right hand stimulus when preceded by a left or right hand stimulus, together with the amount of repetition facilitation for each condition as measured by alternation RT - repetition RT.

	Current stimulus					
Previous stimulus	Direct L	Direct R	Translated L	Translated R	Mixed L	Mixed R
L	490	457	551	611	524	548
R	455	483	598	540	561	486
mean difference (alternation minus repetition)	35	26	47	71	37	62

The interaction effect indicates that the extent of the facilitation from repetition depends on the task. Overall, alternation RT minus repetition RT (a measure of the facilitation) was 31, 59 and 50 msec for the direct, translated and mixed tasks respectively. That is, the facilitation is proportional to the overall task RT.

However, this is an oversimplification as the following discussion of part of the three way interaction, repetition by hand by task, shows.

For the direct and translated tasks (conditions Dd, dD, Tt and tT), the S-R mapping used is repeated on each successive trial, whether the responding hand is the same or an alternation. For the mixed task this is not so: a hand repetition means a mapping repetition but a hand alternation means a mapping alternation in the task used here. Both Duncan (1977) and Smith (1977) predict sequential effects with stimulus repetitions faster than nonrepetitions, but their predictions for the effect of mapping repetitions versus alternations differ. Duncan presented evidence that mapping repetitions were faster than mapping alternations for his inner pair of stimuli for all conditions. He interpreted this in line with his postulated extra "mapping selection stage, which is facilitated by repetition or hampered by having to change mappings on successive trials." Unexpectedly he found no such effect for the outer stimuli, but offers no explanation as to why this was so.

This contrasts with the suggestion put forward in Chapter IV to account for general repetition effects. Recapping briefly, the model accounts for the relationship Td < Tt by postulating that some time is taken by translating "noise" excitation of the latent stimuli to their responses. (Latent stimuli are the stimuli in the task not given on this trial). As this process takes more time for t than for d, and the overall RT is the translation time for all the stimuli, we get Td < Tt. Mutatis mutandis, tD > dD. It was suggested that the "noise" excitation may be spread unequally amongst the possible stimuli with the previous stimulus having a larger share. That is, the origin of the noise may be at least in part the residual excitation uncleared from the previous stimulus. Under this postulate, if the stimulus or response is repeated, it is primed by the residual excitation i.e. needs to accumulate less excitation to reach its criterion, and hence repetitions are faster. On trials which are nonrepetitions, it is a latent stimulus which is primed, and the time to transform this retards the correct response. In the accelerating model, we should expect less retardation if the mapping rule for the preceding stimulus is easy than if it is hard.

If Duncan is correct, repetition facilitation measured by alternation RT minus repetition RT will be greater in the mixed task than in the equivalent unmixed control for both S-R associations. An alternation in both mixed and unmixed tasks involves an alternation in the hand of the stimulus, but in the mixed tasks involves an alternation in S-R mapping as well which takes more time than the repeated mapping in the nonmixed task. Repetitions are equivalent in both mixed and unmixed tasks. Thus repetition facilitation should be greater in a mixed task than an unmixed for both mappings.

The opposing prediction from the accelerating cycle model is that repetition facilitation for the direct mapping is greater in the mixed task than in the unmixed direct task, <u>but</u> is less in the mixed task than in the unmixed (translated) task for the translated mapping. For the direct mapping in the mixed task, an alternation means that the preceding stimulus used the translated mapping so noise is higher on a latent translated stimulus which gives a longer RT when compared with the same situation in the unmixed direct task. For the translated mapping in the mixed task, an alternation means that the previous stimulus used the direct mapping which takes less time than if it had needed the translated mapping on the other hand. That is, the facilitation is less in the mixed than the nonmixed translated task.

The comparisons then, are between the repetition facilitation given in Table 6.5, (i) for the right hand on the direct and mixed tasks (26 and 62 msec respectively) as these two involve the same hand and mapping, and (ii) the left hand on the translated and mixed tasks (47 and 37 msec respectively). Both comparisons are significant in the direction predicted by Smith's model (related samples t-test gave $t = -3.6$, $df = 5$, $p = .016$ and $t = 9.1$, $df = 5$, $p < .001$ respectively) while (ii) goes in the direction opposite to Duncan's prediction.

5. CONCLUSIONS

In conclusion the between mapping sequential effects found here are as predicted by the model and as such support the suggestion that repetition effects can be explained within the framework of this model as being caused by leftover excitation from the previous stimulus. Overall, the correct prediction of both sequential effects and mean RT rank order of the tasks as found in these experiments must be interpreted as demonstrating the validity of the model's approach to these features of reaction time processing.

CHAPTER VII

THE EFFECT OF SIGNAL STRENGTH AND RESPONSE CRITERION ON THE RELATIONSHIP BETWEEN RT AND N.

1.1 A prediction from the accelerating cycle model

A feature of the accelerating cycle model is that it subsumes two formulations of the logarithmic relationship between RT and the number of alternatives, N, confronting the subject. It predicts that $log(N)$ will fit well for low internal signal-to-noise strength s, or high response criterion r, as compared with $log(N+1)$ for high s or low r. These rival formulations were suggested by Hyman (1953) and Hick (1952a) respectively. Indeed, the new equation says that RT will be proportional to $log(N+D)$ where D ranges between 0 and 1 depending on s and r. This follows from the equation

$$\text{RT} = A + B.log(N + \frac{s}{r}) \qquad 7.1$$

where N is the number of alternatives, s is the signal-to-noise strength, r is the response criterion and A and B are empirical constants. Since the value of s can be manipulated by the experimenter ($s > 0$) and it is assumed that r is set by the subject ($r > 0$) so that $r \geqslant s$, (i.e. $\frac{s}{r} < 1$), it follows that $0 \leqslant \frac{s}{r} \leqslant 1$. That is, RT is proportional to $log(N+D)$ where $0 \leqslant D = \frac{s}{r} \leqslant 1$.

In Chapter IV it was pointed out that the RTs obtained by Hyman and fitted by $log(N)$ were to stimuli less intense than those in Hick's experiment, which were fitted by $log(N+1)$. Welford (1968) noted that RTs in a self-paced hights-keys task used by Crossman (1956) were fitted well by $log(N + .45)$, i.e.

intermediate between those of Hick and Hyman. If s in that task was intermediate between that used by Hick and Hyman, then this new formulation would be supported. Certainly Crossman's results can be taken as an indication that values of D between 0 and 1 are possible which is in accord with the new model.

What is needed to test this prediction is an experiment in which a range of values of D are possible and which can at least be ranked a priori. Since $D = \frac{s}{r}$ one can attempt to vary or measure either s or r and measure the resulting RTs. In addition one needs a means of estimating D from the RT data which is independent of A and B in equation 7.1 for otherwise inadequacies in estimating A and B would affect the estimate of D. Such an estimate is K, the ratio of the pairwise differences, i.e. $(RT_8 - RT_4)/(RT_4 - RT_2)$. This can be shown as follows

$$RT_N - RT_M = (A + B.log(N+D)) - (A + B.log(M+D))$$

$$= B\ (log(N+D) - log(M+D)) \qquad 7.2$$

Therefore

$$K = \frac{RT_8 - RT_4}{RT_4 - RT_2} = \frac{log(8+D) - log(4+D)}{log(4+D) - log(2+D)} \qquad 7.3$$

The only parameter affecting K is D, and so the value of K can be tabulated for a range of D values and compared with the calculated value of K from sets of trials for which D is assumed constant. Such tabulation shows that K is monotonically increasing with D, as given in appendix 7,

2. ANALYSIS OF AN EXPERIMENT BY HUTT, NEWTON AND FAIRWEATHER (1977)

The first experiment considered here is one in which D was manipulated via s, the signal-to-noise strength. The data presented by Hutt, Newton and Fairweather (1977) can be used for this. Their subjects were twenty children with epilepsy, and their task was a choice reaction one with visually presented numerals as the stimuli and key presses as responses. Each subject was run under three conditions, N = 2, 4 and 8. While the subjects were performing the task, simultaneous EEG recordings were made. The EEG activity shown on this record was classified into 7 possible categories, of which only 4 were sufficiently abundant to be useful. These were generalized spike wave (GSW), bilateral spike wave (BSW), localized spike wave (LSW), or background (BG). The full definitions of these categories is given in Hutt, Newton and Fairweather (1977), but the only feature relevant here is that they are listed in decreasing order of severity of abnormality as indicated by the number of recording sites at which spike waves were evident. Mean reaction times were calaculated for responses which were made during each class of EEG activity as were the regression lines of log_2N on RT (RT = $A + B.log_2N$). Their main finding was that the reciprocal of the slope, B, which is the rate of gain of information or channel capacity, was less during GSW than BG. They argue that "GSW activity functions as neural noise reducing the child's rate of gain of information". That is, these results suggest that part of whatever limits channel capacity and has been called "noise" is indeed measurable as neural noise in some circumstances and that the amount of noise is an increasing function of the number of sites showing spike wave activity.

This is one situation in which to look at the effect of s on the measured D, for the external stimulus strength is constant while noise takes various values which we can rank, and hence s can also be ranked, in the reverse order of course. More importantly, since trials in each category come from the same experimental block, it is safe to assume that r is constant, i.e. that the response criterion adopted by the subject does not vary systematically within the block. The importance of this was established in an unsuccessful pilot study in which it was attempted to vary s independently of r. The experiment used two types of stimuli, which were either spatially distinct or diffuse, i.e. occupying only one stimulus position (high s) as against the stimulus position and half of the adjacent two (low s). Blocks of trials with $N = 2$, 4 and 8 were run separately for each stimulus type. Only three subjects were run, but values of K calculated from the RTs showed no clearcut effect of stimulus type. It was thought that the expected pattern had been clouded by subjects' varying r inversely with s as was indicated in debriefing. All three subjects said that they had to slow down and be more cautious with the diffuse stimuli so as not to make mistakes, that is, they effectively changed r between stimulus types. As there could be no guarantee that subjects would maintain r between conditions, that experiment was not continued.

The study of Hutt et al. would seem to avoid this confounding. The accelerating cycle model predicts that, since D decreases with increasing noise, the calculated values of K should decrease from BG to GSW conditions. The mean RT_N for BG and GSW can be taken from their table 2 for 11 subjects individually and tested against the prediction that K will be smaller for the high noise GSW than for the low noise BG trials. Values of K were not calculated for S6, since that subject made no responses during GSW in the 2 choice task; nor for S13, who made a total of only 9 responses during GSW in the 2, 4 and 8 choice tasks combined, so that his GSW RTs were considered to be unreliable. The prediction held for 9 of the 11 subjects and this outcome is favourable to the model ($p = .033$ for a one tailed binomial test). Substitution into equation 7.3 shows that K increases from 1.0 to 1.15 as D increases from 0 to 1. Thus ideally all values of K should lie in the range 1.0 to 1.15 but most calculated here were outside this, ranging from .41 to 1.97 with a mean of 1.00 for BG and -.26 to 2.33 with a mean of .78 for GSW as shown in Table 7.1. This variability may reflect genuine individual differences, or may reflect errors of estimation compounded by the number of arithmetic operations performed on the raw means to produce K. For example, the variance of the estimate of $RT_8 - RT_4$ is the sum of the variances of RT_8 and RT_4, and similarly for $RT_4 - RT_2$. The relative variance and hence standard error of estimate is increased still further by taking their ratio. That the phenomenon shows through this variability attests to its robustness.

TABLE 7.1: Values of K calculated using equation 7.3 from the RT data of 12 subjects under two conditions as reported by Hutt, Newton and Fairweather (1977). The accelerating cycle model predicts that K will be larger in the low noise EEG condition, BG, than in the high noise, GSW.

See text for the explanation of K, BG and GSW.

	"Noise" level	
Subject	BG (low)	GSW (high)
1	.71	.33
2	.96	.61
3	1.78	1.29
4	.68	.01
5	1.10	1.38
6	Insufficient Data	
7	1.97	1.19
8	.41	.30
9	.79	- .26
10	1.57	.85
11	1.57	.85
12	.52	2.33
Mean	1.00	.78

It is recognised that epileptics present an extreme case of neural noise and so any extrapolation of these results to healthy populations can only be tentative. However, given that normals show changes in EEG activity to a wide range of stimuli (see Price & Smith's 1974 bibliography of event related potentials), it is tempting to suggest that extraneous stimuli, internal or external, may produce localized increases in brain activity analogous to spike wave activity in epileptics. Indeed, if the pathway from the stimulus area to the response area in the brain is long, activity in the two areas may cause mutual interference increasing the noise and reducing the channel capacity.

3. EXPERIMENT 7

In the second experiment, the response criterion, r, was varied as a within subject parameter. The model predicts that D is inversely proportional to r, i.e. D and hence K is smaller if the subject responds cautiously, emphasizing accuracy (high r), than if responses are made emphasizing speed (low r). It follows that K should be smaller when calculated from accuracy RTs than from speed RTs. This was tested in the following experiment.

3.1 METHOD

Subjects. Eight first year Psychology I students, 4 male and 4 female, between the ages of 20 and 24 acted as subjects as part of a course requirement. They were all unaware of the purpose of the experiment.

Apparatus. The 8 lens topped neon lights and 8 response keys described in Chapter II were used in this experiment.

Procedure. Each subject was run under two conditions, namely accuracy and speed. In the former, subjects were asked to respond quickly but without making more than about 2 errors in each block of 192 trials, and it was stressed that accuracy was more important than speed. For the speed condition, the subjects were requested to respond as fast as possible, making about 10 errors per 192 trials, with speed being more important than accuracy.

All subjects did 64 familiarization trials as described in experiment 1. In this, subjects responded with the compatible key to the lights as they came on in a prearranged order. This acquainted the subjects with the apparatus without practising directly the choice tasks to follow. Each subject then was given 6 blocks of 192 trials, being N = 2, 4 and 8 choice under accuracy and speed conditions. Within each block each of the N stimuli occurred randomly but equally often in each 48 trials. The order of giving the blocks was counterbalanced so that 4 subjects did 2, 4 and then 8 choice and four received the reverse order, with half of each group given accuracy instructions first and speed second, and vice versa for the rest.

3.2 RESULTS AND DISCUSSION

The mean correct RTs for each subject were used to calculate K for each individual as in equation 7.3 under both conditions. The mean RTs, percentage errors and K values are given in Table 7.2. With one exception, all subjects made fewer errors under accuracy instructions and were faster with speed instructions as is shown in Table 7.2, which gives prima facie evidence that subjects did indeed

TABLE 7.2: The mean RT (msec) percentage errors and K values obtained in experiment 7. All subjects were faster in the speed condition, and made fewer errors in the accuracy condition, except that subject 6 made 1 error in the 2 choice accuracy condition, and none in the 2 choice speed. K is larger in the speed condition as predicted by the accelerating cycle model, except for subject 8.

	INSTRUCTIONS							
	Speed				Accuracy			
	N			K	N			K
Subject	2	4	8		2	4	8	
1	267(2)	294(16)	389(22)	3.52	282(0)	331(2.5)	431(5.5)	2.04
2	306(.5)	400(3)	506(2)	1.13	342(0)	459(2)	534(1.5)	.64
3	246(8.5)	333(17)	382(20)	.56	301(1.5)	439(2)	505(4)	.48
4	240(2.5)	394(5)	484(10.5)	.58	284(.5)	539(1.5)	666(1.5)	.50
5	281(2.5)	401(4)	484(10.5)	.69	318(0)	459(1.5)	545(.5)	.61
6	393(0)	447(8.5)	535(8.5)	1.69	380(.5)	486(2.5)	591(6)	.99
7	250(4.5)	297(10.5)	358(17)	1.30	269(2)	337(4.5)	404(5.5)	.99
8	311(2.5)	481(7.5)	533(5.5)	.31	369(1)	490(2.5)	551(3)	.50
Mean				1.22				.85

set r higher in the accuracy condition. The one exception was that subject 6 made one more error and was 13 msec faster in the accuracy than in speed conditions for the 2 choice.

The prediction that K would be smaller for accuracy trials was accurate for all but subject 8. This is statistically significant (p = .035 on a one-tailed binomial test). It is possible that subject 8 changed her response criterion within an instruction set, which would upset the value of K. This possibility is strengthened since subject 8 had the most variable speed-accuracy metric as noted below.

So once again, variation of a parameter postulated as affecting D had the effect predicted by the model. Again, values of K did not obey the strong prediction of being between 1.0 and 1.15, but the variability was less than for the epileptic subjects of Hutt et al., as would be expected since each RT was based on more trials in this experiment. The mean K for both conditions was near the predicted range for these results also (K = 0.85 and 1.22 for accuracy and speed respectively). Taken together the two experiments provide good evidence for the validity of this aspect of the model. That is, RTs from a subject responding to a strong stimulus or with low caution will be better fitted by $log(N)$ than $log(N+1)$ and vice versa if he responds to weak or noisy stimuli or with high accuracy. This suggests that this model may be a relevant framework for investigating speed/accuracy tradeoffs, although more attention would need to be given to error producing aspects of processing than the model currently covers.

4. A POSSIBLE METRIC FOR SPEED-ACCURACY TRADEOFF

Previous workers have shown that RT varies with instructions for speed, accuracy or both, and in general have found that RT is proportional to H_t, the information transmitted. However, such studies have used only one N (e.g. Howell & Kreidler 1963, N = 10; Fitts 1966, N = 15; Lappin & Disch 1972, N = 2). Pew (1969) noted that statistical decision models, i.e. broadly those which postulate a progressive accumulation of evidence during each trial, predict an orderly tradeoff between speed and accuracy. He suggested that if a Bayesian approach was adopted, a linear increment in evidence in favour of a given stimulus would produce a logarithmic increase in the posterior odds. Since RT is the time to accumulate sufficient evidence for one alternative, it seemed plausible to investigate the correlation of RT with the logarithm of the posterior odds where odds can be measured as the ratio of correct responses to errors, i.e. to check whether

$$\mathrm{RT} \propto \log \frac{\textit{number of correct responses}}{\textit{number of errors}} \qquad 7.4$$

Empirically this seemed to be correct in a range of studies he reviewed. Each of these studies varied the error rate and hence the odds by manipulating the payoffs and penalties for responses faster or slower than an experimenter-set deadline, and for errors within one task. The degree of choice used was constant within each study but varied between. The effect of increasing N, i.e. the between studies comparisons was to move the straight line derived from equation 7.4 down and to the right. This reflects the change in the odds for chance performance as *N* increases, which is 1:*N*-1 for any *N*, which reduces as *N* increases, thus moving the fitted line downwards.

This approach was tried on the data gathered in this experiment. For each subject, six pairs of values were obtained, being the RT and *log*(odds) for *N* = 2, 4 and 8 under both speed and accuracy instructions. For each of the three tasks, i.e. *N* = 2, 4 and 8, there were only two points measured, and since there is a straight line passing exactly through any two points, the goodness of fit of Pew's hypothesis could not be assessed. However the slope of the line for each task can be estimated from the two points. These values are given in Table 7.4. No consistency or pattern was apparent in the data, unlike the studies compared by Pew, all of which involved the subjects being constrained to respond before a deadline imposed by the experimenter or be penalised. In the experiment reported here, no deadline was enforced, and the only restriction was to respond quickly or accurately, depending on the condition. This difference in procedures may explain why Pew's approach was not useful in this study.

An alternative metric was therefore tried, entailing measuring the cost in time of making an error, rather than the question Pew investigated, "how long does it take to increase the confidence of one's judgement by a constant factor?" Pew discarded the measure to be tried here as not meaningful for the deadline situations he analysed.

TABLE 7.3: *The speed-error tradeoff score, T, in msec per error for N = 2, 4 and 8.*

See text for discussion of these results.

Subject	Number of alternatives 2	4	8	mean
1	3.8	3.4	3.8	3.6
2	36.0	30.0	28.0	31.2
3	3.9	3.5	3.8	3.7
4	11.0	20.7	10.1	13.9
5	7.4	11.6	3.1	7.4
6	13.0	3.3	10.6	8.9
7	3.8	5.0	2.0	3.6
8	19.3	0.9	3.6	7.9
mean	12.3	9.7	8.1	

TABLE 7.4: *The slope of the line joining the two RT and log(odds) points for each degree of choice is given in the table below. The raw data comes from experiment 7 and is listed in Table 7.2. The four missing values could not be calculated since no errors were made which meant that the odds could not be estimated.*

Subject	N 2	4	8
1	-	69.5	128.0
2	-	325.9	220.5
3	70.0	105.4	157.3
4	62.1	269.0	204.9
5	-	132.7	44.5
6	-	69.6	325.2
7	52.2	175.4	83.8
8	143.2	17.9	65.6

The data collected in this experiment allow some preliminary assessment of this aspect of speed-accuracy tradeoff, namely the comparative tradeoff for various *N*. For *N* = 2, 4 and 8, shortening RT increased the number of errors for all subjects as expected, and the metric chosen for study here was *T*, the time gained for each additional error made. That is, the difference between the RTs for speed and accuracy instructions was divided by the difference in the number of errors made. For example, if the subject made 8 errors in response with a mean correct RT of 378 msec in the speed conditions, and only 4 errors with an RT of 390 msec in accuracy conditions, then *T* would equal 3 msec per error, i.e. (390 - 378)/(8 - 4). That means that the subject gained 3 msec in response in speed for each additional error he made.

There is no existing result onwhich to base a prediction as to what pattern *T* would show, but the simplest hypothesis is that *N* would have no effect, i.e. lowering the response criterion to allow 1 more error would reduce RT by the same amount whether there were 2, 4 or 8 alternatives. Table 7.3 presents *T* values for each subject's 2, 4 and 8 choice data which is shown in Table 7.2. An analysis of variance on this data showed no significant *N* effect ($F = 1.5$, $df = 2,14$, $p = .26$). That is, there is a suggestion in the data presented here that the speed gained per error is fixed whether the subject is faced with 2, 4 or 8 alternatives. This equality is particularly striking for subjects 1, 2 and 3, whose three *T* values are very similar, as are two of the three for subjects 4, 6 and 7. Only two of the subjects show three widely different values, namely subjects 5 and 8. Subject 8's *K* data was also an exception. However there is a good deal of difference between subjects, with mean *T* ranging from 3.6 to 31.2. Perhaps this is a feature of an individual's processing, with some subjects habitually gaining a lot from reducing their criterion by one error while others gain little.

If further experimentation showed such individual differences to be consistent over a range of tasks, this result may have useful applications. For example, it suggests that people will benefit differently from training procedures according to their *T* score. People with a high *T* would gain more from being trained to work at the error rate appropriate to their task than would people with a low *T*.

Overall this result is intrinsically interesting and worthy of further study, for example, to investigate the difference between situations in which Pew's analysis is useful, and those in which the metric *T* is useful, but a discussion of any theoretical implications based on one experiment would be premature.

CHAPTER VIII

CONCLUSIONS

The accelerating cycle model of CRT proposed in Chapter IV has been shown to explain satisfactorily a wide range of findings. In experiments 1 and 2 it was established that there is no increase in RT with *N* for a highly compatible S-R association. This is difficult to explain in terms of other models, but is covered by the accelerating cycle model.

Experiment 3 produced results which are inconsistent with an additive stage approach to RT processing, but could be fitted completely by the accelerating cycle model which incorporates the two principles shown in these results. These were: the temporal uncertainty principle, which says that a response that is called for irregularly will take longer than a regular response; and the latent stimulus effect, in which the RT to the given stimulus is affected by the other possible stimuli to an extent determined by their S-R association. This principle was tested further in experiments 5 and 6, in which subjects were given 2, 4 and 8 choice reaction tasks under 3 conditions; two with different S-R associations and the third, the mixed task, with those two associations applied to different stimuli in the one task. The latent stimulus principle held in the manner predicted by the accelerating cycle model. This was so only after subjects became practised at the task, indicating a limitation of the model. It seems that in early stages of practice in a mixed task subjects adopt a processing strategy which is supplementary to that proposed by the model, involving the selection of the particular S-R association to be used for the given stimulus.

The model also accounts for general repetition effects frequently noted in RT data. That is, if a stimulus is given on two successive trials, it will be responded to faster on the repeated occurrence than if the previous stimulus was different. In addition, the model successfully predicted S-R association repetition effect found in mixed task of experiment 6, where it was noted that a repetition effect was larger in the mixed task than in the unmixed for easy S-R associations and vice versa for hard, which was counter to a prediction by Duncan (1977).

Another feature of the model is that it resolves the difference in the formulations of the RT-N relationship favoured by Hick (1952a), i.e. RT = $k.log(N+1)$, and by Hyman (1953), RT = $a + b.log(N)$. These two become extreme forms of the one relationship, RT = $A + B.log(N+D)$ where $0 \leq D \leq 1$. The model states that D is the ratio of the signal strength to the response criterion. Experiment 7 confirmed that the level of the response criterion did affect D as expected, and the results of Hutt, Newton and Fairweather (1977) were reanalysed to show that the effect of signal strength was as predicted.

One assumption made in developing the model was that extraneous neural activity or "noise" was constant for all degrees of choice. Experiment 4 verified this assumption.

Precise predictions have not been developed from the model in other areas. For example, although the model predicts the general form of changes in RT with practice and the speed-accuracy tradeoff, it does not give quantitative predictions relating the level of practice or speed-accuracy tradeoff to RT. The model is designed to be extended by adding further parameters to describe the precise effects of other variables. For example, once the effect of practice becomes determined in the context of this model, it can be included as an additional parameter with specified interactions with existing parameters.

All in all, the accelerating cycle model accounts for a considerable area of RT research better than other models, and can act as the basis for further research, with new results being incorporated into its structure as their interactions with the model's current parameter set becomes clear.

APPENDICES - INDEX

APPENDIX 1: EXPERIMENT 1

A : Mean correct RTs for individual subjects on the 1, 2, 4 and 8 choice compatible VT task.

	DAY 1				DAY 2			
	N				N			
Subject	1	2	4	8	1	2	4	8
order a (1,2,4,8)								
1	177	237	255	242	168	205	203	211
2	171	222	204	218	164	188	171	192
3	174	241	236	246	168	222	194	212
order b (8,4,2,1)								
4	184	221	244	266	180	210	187	207
5	228	239	236	266	200	219	206	219
6	150	185	206	234	150	230	172	221
order c (4,8,1,2)								
7	162	201	220	205	160	191	189	203
8	217	259	349	318	220	216	206	219
9	175	230	277	271	179	245	232	261
order d (2,1,8,4)								
10	208	315	274	288	198	221	193	180
11	263	276	290	297	259	248	288	281
12	180	210	197	226	131	156	176	197

APPENDIX 1 (continued)

B: Latin square analysis of variance of mean correct RTs from day 2 of experiment 1.

Source	df	Mean Square	F
Between Subjects			
(a) Groups	3	867.4	.2
(b) Subjects within groups	8	3610.8	
Within Subjects			
(c) Order	3	112.6	.7
(d) N	3	3173.2	20.6*
(e) Order by N	6	739.5	4.8*
(f) Error	24	154.2	

*significant at $\alpha = 0.05$

APPENDIX 2

A. *Descriptive statistics on RTs for individual subjects in each condition in Experiment 2. Measurements are in msec., and are given in the order mean correct RT, standard deviation and percentage of errors.*

Stimulus type	Subject	Sex	Order	N = 2	N = 4	N = 8
VT	1	M	2,4,8	664,490,30	820,740,24	763,312,15
	2	M	2,4,8	516,112, 5	444,150, 2	470,103, 3
	3	M	4,8,2	542,281,13	728,190, 7	662,236, 9
	4	M	4,8,2	493,214, 7	572,133, 4	514,159, 3
	5	M	8,2,4	285, 85, 3	268,160, 6	362, 80, 2
	6	M	8,2,4	308,187,18	326, 73,10	357, 99,20
Lights	7	M	2,4,8	654,248, 3	743,243,28	843,259 31
	8	M	2,4,8	740,581,20	909,575,30	1597,743 30
	9	M	4,8,2	556,137, 4	951,200, 3	1057,331 10
	10	M	4,8,2	461,190, 6	634,140,10	902,315 9
	11	M	8,2,4	596,195, 1	749,253, 7	1242,325 15
	12	M	8,2,4	626,171, 3	832,279, 3	1139,326 4
VT	13	F	2,4,8	535,111, 2	618,133, 3	576,152, 3
	14	F	2,4,8	816,165, 1	757,175, 2	768,183, 4
	15	F	4,8,2	418,167, 6	580,175, 6	502,178, 7
	16	F	4,8,2	645,173, 1	676,173, 3	612,161, 5
	17	F	8,2,4	522,272, 8	497,162, 6	569,180, 3
	18	F	8,2,4	448,283,11	547,371,14	615,125,12
Lights	19	F	2,4,8	487,115, 3	838,223, 7	942,346,16
	20	F	2,4,8	432, 91, 1	559,142, 1	791,290, 5
	21	F	4,8,2	552,163, 1	736,232, 2	942,338, 4
	22	F	4,8,2	530,114, 3	812,208, 2	1010,263, 6
	23	F	8,2,4	539,178, 2	966,445, 4	950,227,10
	24	F	8,2,4	503,118, 5	825,273,11	1089,285,13

APPENDIX 2 (continued)

B. Analysis of variance of correct RTs from Experiment 2, with four factors, stimulus type (VT or lights), by N (2, 4 or 8), by order, by sex. Two effects were significant at the .05 level, N and N by stimulus type.

Source	Degrees of freedom	Mean Squares	F	P
N	2	433,002	54.0	.0013
Subjects(S)	12	40,992		
Order (O)	2	48,437	1.2	.34
Sex (X)	1	115	.002	.96
Stimulus Type(T)	1	1,103,850	9.1	.09
NS	24	9,381		
NO	4	8,012	.9	.50
NX	2	10,010	2.5	.19
NT	2	291,704	111.2	.0003
OX	2	43,969	1.1	.37
OT	2	121,361	2.9	.09
XT	1	152,260	3.3	.21
NOX	4	3,937	.4	.79
NOT	4	2,623	.2	.89
NXT	2	9,867	2.9	.17
OXT	2	45,851	1.1	.36
NOXT	4	3,381	.4	.83

APPENDIX 2 (continued)

C. *Analysis of variance of correct RTs from the VT stimulus conditions of Experiment 2, with three factors, N by order by sex.*

Source	Degrees of freedom	Mean Squares	F	P
N	2	13,404	2.2	.22
S	6	38,278		
O	2	163,525	4.3	.07
X	1	79,336	1.7	.32
NS	12	2,912		
NO	4	5,988	2.1	.15
NG	2	572	3.7	.12
OG	2	45,797	1.2	.37
NOG	4	154	.005	.99

APPENDIX 3

A: *Individual subject's mean response times to the comparison response common to all 5 tasks are given in the first five columns. X_2 and B_2, the RT to the other stimulus given in x and b are also listed.*

Subject	Day	A	X	T	B	C	X_2	B_2
1	1	225	225	250	305	313	237	331
	2	202	213	263	250	302	241	252
2	1	188	204	320	281	270	245	297
	2	189	180	254	280	317	200	277
3	1	151	157	197	181	199	181	196
	2	160	162	204	213	248	170	201
4	1	219	153	243	247	307	188	262
	2	146	164	232	184	243	202	184
5	1	190	191	218	203	237	189	215
	2	168	172	173	196	215	180	201
6	1	176	187	193	213	293	213	225
	2	165	175	191	242	237	220	243
7	1	190	173	200	218	237	178	227
	2	185	173	180	191	216	175	195
8	1	202	228	225	255	256	255	240
	2	208	211	247	243	313	267	240
9	1	134	131	151	163	185	281	158
	2	126	119	138	156	196	143	153
10	1	118	123	145	153	174	147	155
	2	121	111	141	159	196	127	153

APPENDIX 3 (continued)

B: *Table of analysis of variance on RTs from Experiment 3, showing that the task effect was significant.*
The model used was $X_{ijk} = T_i + S_{jk} + O_k + TS_{ijk} + TO_{ik} + e$ *using the notation from Winer (1962).*

Source	Degrees of freedom	Mean Squares	F	P
Task type (T)	4	111,96	48.5	<.0001
Subjects (S)	5	3,640		
Order (O)	4	13,103	3.6	.12
TS	20	230.7		
TO	16	357.1	1.5	.18

APPENDIX 4: STUDIES OF COMPATIBILITY AND A NEW MODEL OF CHOICE REACTION TIME.

Paper given at the Sixth International Symposium on Attention and Performance, Stockholm, Sweden, July 28 - August 1, 1975.

Published in "Attention and Performance VI", S. Dornic (Ed.), Hillsdale, New Jersey: Lawrence Erlbaum. pp.27-48.

Smith, G. A. (1975). Studies of compatibility and a new model of choice reaction time. In S. Dornic (Ed.), *Attention and Performance VI,* (pp. 27-48). Hillsdale, New Jersey, Lawrence Erlbaum.

NOTE:

This publication is included in the print copy
of the thesis held in the University of Adelaide Library.

APPENDIX 5.

A. *The effect of SOA (10 to 135 msec) on RT for each degree of choice was analysed by a one-way analysis of variance for individual subjects. The resulting F ratios and associated probabilities are given in the table below. Those entries marked with an asterisk are not significant at the .10 level.*

	N					
	2		4		8	
Subject	$F_{8,207}$	p	$F_{8,207}$	p	$F_{8,207}$	p
1	4.1	<.001	6.2	<.001	7.2	<.001
2	1.7	.09	4.6	<.001	7.6	<.001
3	1.8	.08	.7	.68 *	2.5	.01
4	1.9	.06	1.9	.06	.05	1.0 *
5	10.9	<.001	5.6	<.001	2.0	.04
6	.41	.92 *	1.1	.38 *	1.3	.23*
7	10.9	<.001	9.3	<.001	15.6	<.001
8	3.3	.002	1.8	.08	2.3	.02
9	4.9	<.001	.36	.94 *	.67	.72 *

APPENDIX 5 (continued)

B. *Correct and error RTs in msec for individual subjects and the probability associated with a one-tailed unrelated t-test values for the comparison, correct versus error RTs.*

For the entries marked with an asterisk, correct RTs are not significantly shorter than errors at the .05 level. Double asterisk indicates errors faster than correct responses.

	N					
	2		4		8	
Subject	Correct, Error RTs	p	Correct, Error RTs	p	Correct, Error RTs	p
1	322, 497	.001	482, 577	.003	638, 947	.001
2	282, 393	.01	428, 770	.001	538, 809	.001
3	409, 630	.001	558, 597	.05	630, 708	.004
4	356, 448	.02	624, 732	.004	771, 922	.003
5	746, 1591	.001	1131, 1846	.001	974, 1592	.001
6	301, 308	.35*	335, 316	**	410, 372	**
7	737, 1271	.001	785, 1294	.001	1026, 1720	.001
8	286, 297	.30*	507, 549	.05	500, 568	.003
9	767, 1300	.001	931, 818	**	1036, 1040	.41*

APPENDIX 5 (continued)

C. *Analysis of variance on RT for inner versus outer stimuli (IO) by stimulus duration (SOA). The 4 outer stimuli were those corresponding to the index and little finger responses on each hand, and the inner stimuli with the other 4.*

Source	*MS*	*degrees of freedom*	*F*	*p*
IOI	*245,643*	*1*	*32.7*	$< .001$
SOA	*112,469*	*9*	*14.9*	$< .001$
IO X SOA	*12,202*	*9*	*1.6*	*.13*
Residual	*7,507*	*60*		

APPENDIX 6

A: Mean correct reaction times in msec for individual subjects under each condition, with error response percentages in parentheses. The data from experiment 5 which used vibrotactile stimuli.

CONDITION

	Direct		*Translated*		*Mixed*	
	right	*left*	*right*	*left*	*right*	*left*
Subject	*dD*	*Dd*	*tT*	*Tt*	*tD*	*Dt*
1	*164(5)*	*160(6)*	*414(18)*	*398(16)*	*292(9)*	*389(22)*
2	*342(7)*	*348(0)*	*659(14)*	*670(7)*	*481(1)*	*649(7)*
3	*230(2)*	*210(6)*	*479(12)*	*435(6)*	*271(0)*	*340(15)*
4	*243(1)*	*235(1)*	*543(5)*	*559(8)*	*359(3)*	*513(8)*
5	*317(2)*	*319(1)*	*592(12)*	*592(1)*	*382(5)*	*561(13)*
6	*263(2)*	*246(2)*	*569(5)*	*561(9)*	*381(7)*	*528(8)*
Overall mean	*260(3)*	*253(3)*	*543(11)*	*536(8)*	*361(5)*	*498(12)*

APPENDIX 6 (continued)

B: Mean correct reaction times in msec for individual subjects under each condition, with error responses percentages in parentheses. The data is from experiment 6, day 2, using neon lights as stimuli.

	CONDITION					
	Direct		*Translated*		*Mixed*	
	right	*left*	*right*	*left*	*right*	*left*
Subject	*dD*	*Dd*	*tT*	*Tt*	*tC*	*Tc*
7	*399(4)*	*383(6)*	*535(9)*	*518(6)*	*454(5)*	*471(5)*
8	*404(4)*	*414(8)*	*498(6)*	*502(5)*	*454(10)*	*470(11)*
9	*544(5)*	*532(4)*	*591(4)*	*605(6)*	*563(11)*	*601(3)*
10	*517(5)*	*531(5)*	*609(8)*	*616(4)*	*560(13)*	*581(8)*
11	*480(6)*	*476(5)*	*573(7)*	*568(5)*	*546(9)*	*570(6)*
12	*497(5)*	*491(7)*	*656(8)*	*647(5)*	*539(9)*	*625(9)*
Overall mean	*474(5)*	*471(6)*	*577(7)*	*576(5)*	*519(9)*	*553(7)*

APPENDIX 6 (continued)

C: *Analysis of variance of correct reaction times with four factors: repetition/alternation of stimulus (R), left/right hand (H), S-R association (M), and subjects (S).*

See text for the interpretation of the results. The three effects starred are significant at the .05 level.

Source	df	Mean Square	F	p
* R	1	11,603	82.6	.0003
H	1	1,168	1.7	.25
* M	2	65,116	34.4	<.0001
S	5	34,397		
S X R	5	140		
S X H	5	685		
S X M	10	1,893		
R X H	1	910	6.1	.06
* R X M	2	14,469	75.9	<.0001
H X M	2	1,531	2.1	.18
S X H X M	10	739		
S X R X H	5	150		
S X R X M	10	190		
R X H X M	2	591	3.1	.09
S X R X H X M	10	193		

APPENDIX 6 (continued)

D: Sequential effects for individual subjects from the data of day 2, experiment 6 (lights as stimuli). Each correct response was categorized by the current and the previous stimulus hand, i.e. left following left, left/right, right/left and right/right. The means of these is given in the table below.

TASK	Previous stimulus	Current stimulus: Left		Current stimulus: Right	
DIRECT	Left	413 (S.7)	525 (S.10)	371	515
		422 (S.8)	496 (S.11)	398	463
		577 (S.9)	510 (S.12)	509	484
	Right	384	505	393	546
		387	468	427	487
		505	481	548	499
TRANSLATED	Left	491	596	584	641
		467	540	533	617
		578	631	606	683
	Right	544	640	483	566
		534	588	460	522
		629	656	577	629
MIXED	Left	450	569	484	589
		457	564	464	578
		496	618	608	563
	Right	492	608	419	330
		512	591	439	514
		527	634	505	509

APPENDIX 7: Values of K for selected values of D, calculated from the data of experiment 7, using equation 7.3 (p.146).

Note that K increases monotonically with D.

D:	-1.0,	-0.75,	-0.50,	-0.25,	0,
K:	.77,	.84,	.90,	.95,	1.00,

D:	.1,	.2,	.3,	.4,	.5,
K:	1.02,	1.03,	1.05,	1.07,	1.08,

D:	.6,	.7,	.8,	.9,	1.0 ,
K:	1.10,	1.11,	1.12	1.14,	1.15,

D:	1.25,	1.50,	1.75,	2.00
K:	1.18,	1.21,	1.24,	1.26

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